

THE APPLICATION OF ADAPTIVE SAMPLING AND ANALYSIS  
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October 1999By  
Robert Johnson  
Karen P. Smith  
John Quinn

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Environmental Assessment Division  
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The Application of Adaptive Sampling and Analysis Program (ASAP) Techniques to  
NORM Sites\*

By  
Robert Johnson  
Karen P. Smith  
John Quinn

Argonne National Laboratory  
Environmental Assessment Division  
9700 S. Cass Avenue  
Argonne, IL 60439

Prepared for  
U.S. Department of Energy  
Assistant Secretary for Fossil Energy

John K. Ford, Technology Manager  
National Petroleum Technology Office  
P.O. Box 3628  
Tulsa, OK 74101

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## NOTATION

The following is a list of acronyms, abbreviations, and initialisms (including units of measure) used in this document.

### ACRONYMS, ABBREVIATIONS, AND INITIALISMS

ACL	Analytical Chemistry Laboratory
ANL	Argonne National Laboratory
ASAP	Adaptive Sampling and Analysis Program
CERCLA	Comprehensive Environmental Restoration and Liability Act
DEQ	State of Michigan Department of Environmental Quality
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
E&P	Exploration and Production
FIDLER	Field Instrument for Detecting Low Energy Radiation
HPGe	High Purity Germanium
GIS	Geographic Information System
GPS	Global Positioning System
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
NaI	Sodium Iodide
NORM	Naturally Occurring Radioactive Materials
NORM IS	NORM Instruments and Services
QA/QC	Quality Assurance/Quality Control

### RADIONUCLIDES

K-40	potassium-40
Ra-226	radium-226
Ra-228	radium-228
Th-232	thorium-232
U-238	uranium-238

### UNITS OF MEASURE

cm <sup>2</sup>	square centimeter(s)	m <sup>2</sup>	square meter(s)
cpm	counts per minute	mrem	millirem
ft	feet (foot)	rem	roentgen equivalent man
pCi	picocurie(s)	s	second(s)
g	gram(s)	yd <sup>2</sup>	square yard(s)
h	hour(s)	yd <sup>3</sup>	cubic yard(s)
m	meter(s)		

## SUMMARY

Adaptive Sampling and Analysis Program (ASAP) data collection relies on real-time data collection technologies and in-field decision support to guide the course of characterization and/or remediation work. ASAP techniques have particular application to naturally occurring radioactive materials (NORM) problems because of the relative abundance of real-time technologies appropriate for radium-226 (Ra-226). Demonstration work at a Michigan site made use of three real-time data collection technologies operating in an Adaptive Sampling and Analysis framework. These included a gamma radiation detecting walkover/Global Positioning System (GPS) for complete surficial site coverage; *in situ* High Purity Germanium (HPGe) gamma spectroscopy for quantitative isotope specific direct measurements; and a sodium iodide (NaI)-based direct measurement device called RadInSoil™, specifically intended for NORM work.

The results from the Michigan demonstration establish that this type of approach can be very effective for NORM sites. The advantages include (1) greatly reduced per sample analytical costs; (2) a reduced reliance on soil sampling and *ex situ* gamma spectroscopy analyses; (3) the ability to combine characterization with remediation activities in one fieldwork cycle; (4) improved documentation; and (5) ultimately better remediation, as measured by greater precision in delineating soils that are not in compliance with requirements from soils that are in compliance. In addition, the demonstration showed that the use of real-time technologies, such as the RadInSoil, can facilitate the implementation of a *Multi-Agency Radiation Survey and Site Investigation Manual* (MARSSIM)-based final status survey program.

In terms of individual technologies and their performance, the gamma walkover data provided relatively inexpensive, complete coverage of surficial soils with excellent correlation with Ra-226 concentrations. The RadInSoil exhibited accuracy for Ra-226 that compared favorably with intralaboratory accuracy results at greatly reduced per sample costs and at the same time yielded acceptable precision for measuring Ra-226 at 5 pCi/g. The *in situ* HPGe systems also produced results that were less costly than *ex situ* gamma spectroscopy analysis of soils samples, while yielding isotope-specific concentrations of comparable quality to *ex situ* analyses. The *in situ* HPGe systems also provided data that were more directly comparable with the definitions of cleanup requirements than data obtained from discrete sample results.

A partial explanation for the excellent performance observed was the fact that the Michigan site was solely contaminated with Ra-226 and its progeny. In some portions of the country, NORM contamination includes Ra-228 as well. The presence of isotopes from more than one decay series above background complicates the use of the RadInSoil and would also reduce the correlation observed between gamma walkover results and cleanup requirements. However, even when Ra-228 is present, the use of these technologies would still yield a conservative cleanup. The *in situ* HPGe is capable of quantifying Ra-226 and Ra-228 individually; consequently, it would likely play a more important role at sites where both Ra-226 and Ra-228 are of concern.





# 1 INTRODUCTION AND BACKGROUND

## 1.1 Introduction

Radiation occurs naturally throughout our environment. In addition to radiation that is derived naturally from the sun and deep space, naturally occurring radioactive materials (NORM) are found in our bodies, the food we eat, the places where we live and work, and the ground we live on. For the most part, humans have adapted to radiation exposures resulting from background concentrations of NORM (i.e., the normal, ambient concentrations of radiation).

Certain industrial processes, however, can cause NORM to accumulate in elevated concentrations that could pose a risk to human health and the environment. The petroleum industry is one of several industries that generate large volumes of NORM-bearing wastes. Most of these wastes have relatively low specific activity levels; some of these wastes, however, may contain higher concentrations of radium and need to be managed safely to limit human health exposures.

In response to the potential risk presented by NORM, states have begun to develop regulations specifically addressing NORM. Among other things, these regulations establish limits on radium content for unrestricted release of land previously impacted by NORM-generating activities. Petroleum industry sites that have become contaminated by elevated concentrations of NORM must be cleaned up to meet specific criteria before they can be released. Although the number of NORM-contaminated petroleum industry sites has not been well documented, one can predict that the number of sites requiring cleanup is large given past waste management practices that allowed wastes to be released to surface soils and the stringency of current cleanup standards.

From a cost perspective, compliance with NORM regulations has the potential to significantly impact the petroleum industry, and other industries, particularly if a large number of sites require cleanup. New opportunities to reduce the costs associated with regulatory compliance need to be explored by the industries that generate NORM wastes. Toward this end, the U.S. Department of Energy (DOE) funded Argonne National Laboratory (ANL) to conduct a field program demonstrating expedited approaches to site characterization and remediation at a NORM-contaminated site. The site selected for this field demonstration was a petroleum industry site located in Michigan that, over time, had been contaminated by NORM-bearing scales. The objective of the field program was to demonstrate to the petroleum industry the potential cost savings of applying these approaches at NORM-contaminated sites.

The expedited approaches demonstrated in the field program were originally developed at ANL to support large-scale cleanup efforts at contaminated sites owned by DOE and the U.S. Department of Defense (DoD). The approaches are part of a methodology that allows characterization of a contaminated site in an Adaptive Sampling and Analysis Program (ASAP) mode. Under the ASAP approach, on-site and *in situ* analytical capabilities are employed to generate data

characterizing contamination at a site in the field. These data are then used to “adapt” or change the characterization program as it moves forward. The ASAP approach results in reduced characterization/remediation costs because field analytics are often less expensive on a per sample basis than traditional *ex situ* off-site soil analyses. The lower expense is also due to remedial work being limited only to those soils that truly require it and to characterization/remediation work that can be bundled into one field effort. In addition, the ASAP approach can result in a better, more thorough remedial action because the process of delineating soils above guidelines from soils that are not can be made more precise.

## **1.2 Background Information on Petroleum Industry NORM**

### **1.2.1 Source and Nature of NORM Contamination**

As a result of oil and gas production and processing operations, NORM sometimes accumulate at elevated concentrations in by-product waste streams. The sources of most of the radioactivity are isotopes of uranium-238 (U-238) and thorium-232 (Th-232), which are naturally present in the subsurface formations from which oil and gas are produced. The primary radionuclide of concern in NORM wastes is radium-226 (Ra-226) of the U-238 decay series (Figure 1.1). Ra-228 of the Th-232 decay series (Figure 1.2) also occurs in NORM waste but is usually present in lower concentrations. Other radionuclides of concern include those that form from the decay of Ra-226 and Ra-228.

The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge. Radium, which is slightly soluble, can be mobilized in the liquid phases of a subsurface formation and transported to the surface in the produced water stream. As the produced water is brought to the surface, some of the dissolved radium precipitates out in solid form. Most commonly, the radium coprecipitates with barium sulfate, a hard and relatively insoluble scale deposit; however, it also can coprecipitate to form other complex sulfates and carbonates.

The radium content in produced water varies geographically. Data collected by the petroleum industry and its regulators suggest that between 10 and 30% of domestic oil and gas wells may produce NORM in elevated concentrations (McArthur 1988; Otto 1989). NORM are a known problem in producing regions along the Gulf Coast, in the Permian Basin (west Texas and southeastern New Mexico), in the Anadarko Basin (northern Texas and southern Oklahoma), in at least one field in Kentucky, and in Michigan (Ashland Exploration, Inc. 1993; Michigan Department of Natural Resources and Department of Public Health 1991; Otto 1989). The radium content in produced water is controlled primarily by the radium content in formation waters. The sedimentary rocks from which oil and gas are produced have varying concentrations of U-238 and Th-232, depending upon their genesis. Radium solubility and mobility appear to be influenced by the salinity of the formation water; higher salinity is aligned with greater solubility.

A variety of factors appear to affect the degree to which radium in solution in produced water will precipitate out in solid form. As the produced water is brought to the surface, it undergoes temperature and pressure phase changes that allow solids to precipitate. In general, radium concentrations tend to be highest closest to the wellhead where these phase changes are greatest. Sulfate content of the produced water also is a factor given the strong correlation between barium sulfate scale and radium precipitation. Wells that do not have significant associated scale formation generally do not have a NORM problem.

Radium that remains in solution is disposed of along with the produced water stream. Most produced water is disposed of via subsurface injection; radium content in reinjected produced water is not regulated. Radium content in scales and sludges, however, is regarded as a waste management issue. Periodically, the scales and sludges that accumulate inside pieces of oil field equipment are removed. This can occur during a routine maintenance activity or when a piece of equipment is taken off line. Radium-bearing scales and sludges can pose a waste management issue if the radium content is high enough. Similarly, pieces of equipment that contain residual quantities of NORM-bearing scales and sludges and surface soils impacted by these wastes can present waste management issues to the petroleum industry.

As described above, at most localities NORM-bearing scales form on the inside of pieces of equipment. In Michigan, however, where the field demonstrations were conducted, scales sometimes form on the outside of pipe used to case a wellbore. This external scaling results because state regulations allow wells to be constructed in a manner that exposes the wellbore casing to subsurface formation waters at certain depths. When this casing is removed from the wellbore, the scales are not contained in any fashion. This situation creates a unique waste management issue, particularly when these scales are NORM-bearing; one result is a greater potential for soil contamination.

### **1.2.2 Regulation of NORM**

Currently, the presence of NORM in petroleum industry wastes is not specifically addressed by any federal regulations. In the absence of federal regulations, individual states have promulgated rules addressing the management and disposal of NORM wastes. These rules have evolved rapidly over the last few years and, at this time, nine states have NORM regulatory programs. Six of these nine states have significant levels of oil and gas production and, while the scope of these regulations typically covers NORM wastes generated by any industry, the primary emphasis is placed on petroleum industry NORM. Several of the major oil and gas producing states still do not have NORM regulations. Of these states, some are currently drafting regulations, others are evaluating the need to do so, and others are waiting on guidance from other organizations. One such organization, the Conference of Radiation Control Program Directors (CRCPD), has developed guideline regulations for states to consider in adopting their own regulatory programs. Other organizations preparing guidelines on NORM regulations include the Health Physics Society and the Interstate Oil and Gas Compact Commission.

The existing state regulatory programs establish standards for (1) NORM exemption or action levels; (2) the licensure of parties possessing, handling, or disposing of NORM; (3) the release of NORM-contaminated equipment and land; (4) worker protection; and (5) NORM disposal. The action levels defining when wastes must be managed as regulated NORM vary from state to state. These levels typically are expressed in terms of radionuclide activity concentrations (in picoCuries per gram, or pCi/g), exposure levels (in microrem per hour, or  $\mu\text{R/h}$ ), surface contamination levels (in disintegrations per minute per 100 square centimeters, or dpm/100m<sup>2</sup>), and radon flux (in picoCuries per square meter per second, or pCi/m<sup>2</sup>/s). Materials exceeding any one of these state-prescribed levels become regulated NORM within that state.

NORM regulations are not consistent from state to state. One fundamental point on which state regulations differ is the radionuclide activity level defining regulated NORM. This level varies from state to state but generally is set at 5 or 30 pCi/g of radium. Table 1.1 provides a partial summary of exemption levels defining regulated NORM in existing or proposed state-level regulations and guidelines; states without significant oil and gas production were omitted from the table. In most states, the level is specific to Ra-226 or Ra-228 concentrations, and it excludes background concentrations of radium. Several states have established two action levels dependant upon the radon emanation rate of the waste. In these states, the action level is 5 pCi/g total radium if the radon emanation rate exceeds 20 pCi/m<sup>2</sup>/s, and 30 pCi/g total radium if the radon emanation rate is below that level. Within an individual state, the soil cleanup standard defining when a piece of land may be released for unrestricted use typically mirrors the exemption level defining regulated NORM; these cleanup standards also are shown in Table 1.1.

### **1.2.3 NORM Management and Disposal Practices**

In the states that have promulgated NORM regulations, operators who generate regulated NORM wastes must comply with a set of management and disposal requirements designed to minimize the potential for adverse human health effects. In general, scales and sludges meeting the definition for regulated NORM must be managed and disposed of by methods that provide a higher degree of containment and isolation than is required for scales and sludges that do not meet this definition. Prior to the promulgation of NORM regulations, all scales and sludges were managed in the same fashion regardless of radium content.

Scales and sludges and other exploration and production (E&P) wastes are not regulated as hazardous wastes; rather, they are managed in accordance with regulations promulgated by state oil and gas regulatory agencies.<sup>1</sup> Under these rules, scales and sludges may be disposed of by a number of

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<sup>1</sup> In 1988, the U.S. Environmental Protection Agency (EPA) determined that most wastes generated by the petroleum industry's E&P activities, including scales and sludges, should be exempted from regulation as hazardous waste under Subtitle C of the Resource Conservation and Recovery Act (RCRA) (EPA 1988). Most states that have been delegated authority to manage the RCRA program have adopted a similar exemption. These wastes can be referred to collectively as "exempt E&P wastes."

mechanisms. The majority of these wastes probably are disposed of by one of two methods: disposal at an industrial landfill, or landspreading, a practice by which wastes are spread over the surface of the ground. In the past, prior to the industry's awareness of NORM issues, scales and sludges containing radium probably were disposed of by release to surface soils. In addition, past management practices for produced water, which can contain elevated concentrations of radium, included surface release.

The extent to which past management practices have contributed to NORM contamination of surface soils has not been quantified. Information collected by the petroleum industry and its regulators defining the number of potentially contaminated sites has not been published. However, given that past practices directly or indirectly resulted in the release of scales, sludges, and produced water to surface soils, one can predict that a large number of sites may have inadvertently become contaminated with concentrations of NORM above natural background levels.

The site used in ANL's field demonstration activities is one example of this type of inadvertent site contamination. At this site, a pipe yard located in Michigan, routine activities unknowingly resulted in contamination of surface soils with elevated concentrations of NORM. In Michigan, scales sometimes form on the outside of casing used to construct wellbores (see Section 1.2.1). Pipes salvaged from producing wells throughout the state were transported to this pipe yard for cleaning, reconditioning, and storage. As is typical at all pipe yards, these pipes were stored on racks throughout the yard. Scales that formed on the outside of the pipes fell off of the pipes during handling and through exposure to the elements. The operators of the wells from which the pipes were derived and the owner of the pipe yard were unaware of the NORM content of the scales. As a result, NORM scales were distributed across the pipe yard.

### **1.3 ASAP Methodology**

ASAPs use real-time data collection techniques and in-field decision making to guide the progress of data collection at hazardous waste sites. An ASAP approach to site characterization/remediation is based on a dynamic work plan that specifies how data collection decisions will be made in the field; it does not, however, specify the exact locations and numbers of samples to be collected. In an ASAP data collection program, *ex situ* off-site analysis of soil samples using standard laboratory techniques is primarily used as a quality assurance/quality control (QA/QC) check for the real-time data; this analysis is not used as the principal data source for decision making. During ASAP data collection, the course of data collection work is driven by the results as they are obtained. In its extreme form, the next sampling location might be determined by all previous results. More commonly in an ASAP data collection effort, data planning and acquisition take place in sequential "chunks." For example, results from one day's work might be used to plan the data collection activities scheduled for the next day. Figure 1.3 graphically illustrates the ASAP process.

ASAPs provide several key advantages over standard characterization approaches that rely on static work plans and off-site analytics. ASAP data collection programs rely on real-time data collection techniques that typically incorporate screening and field analytical technologies. For these types of techniques, per sample analytical costs are typically significantly less than the costs associated with off-site laboratory analyses. ASAP data collection programs can be adjusted in the field as results are encountered, thereby producing data collection programs that are much more focused and efficient than standard gridded approaches. ASAP data collection proceeds until the characterization goals have been met. Consequently, the need for additional site characterization efforts is greatly reduced. In contrast, traditional characterization programs that rely on off-site laboratory analyses for information often require repeated mobilizations to clarify sample results that become available only after the last round of sampling has been completed. Finally, because ASAPs provide data on site in an expedient fashion, characterization and remediation activities can be merged effectively, which shortens project schedules and facilitates the use of more precise remediation technologies. This is particularly true when remediating contaminated soils where ASAP data collection can be effectively used as an *in situ* soil segregation or sorting technique.

ASAP data collection programs require two key components to be effective: (1) real-time data collection techniques appropriate for the contaminants of concern and their cleanup guidelines, and (2) an in-field decision-making methodology for determining the course of data collection in response to real-time data streams.

### **1.3.1 Characterization Technologies Suitable for NORM**

ASAP programs are most effective when there are real-time data collection techniques suitable for contaminants of concern and their cleanup guidelines. Ra-226 and Ra-228 contamination falls squarely in that category. A number of generic technologies are applicable to the characterization of soils contaminated with Ra-226 and/or Ra-228. Some of these are already widely used in a screening mode. Others have been available for some time but have not gained widespread acceptance. Still others are fairly recent technologies that are very promising but not as yet widely used.

Most, if not all, NORM-contaminated sites are contaminated with either Ra-226 and its progeny or with some mixture of Ra-226 and Ra-228 and their progeny. Both isotopes are naturally occurring with background concentrations typically less than 1 pCi/g. Cleanup guidelines for both isotopes are typically concentration based and are expressed in terms of pCi/g (Table 1.1). Typical *in situ* guidelines are 5 pCi/g plus background for surface soils (spatially averaged over 100 square meters and over a 15-centimeter depth profile) and 15 pCi/g for subsurface soils, values that are well above background concentrations. Because of the relatively short half-life of Ra-228, Ra-226 contamination will dominate Ra-228 contamination over time. Traditional laboratory approaches to Ra-226/Ra-228 quantification for soil samples rely on either gamma or alpha spectroscopy. Both techniques have their strengths and weaknesses, and both are generally accepted by the regulatory community. Because most gamma spectroscopy systems actually measure mobile, short-lived progeny

of Ra-226 that are assumed to be in equilibrium with Ra-226, radon emanation from disturbed soil samples can be an issue. *Ex situ* soil sample gamma spectroscopy measurements may underestimate Ra-226 concentrations by as much as 40% for high-radon emanation media if ingrowth is not allowed to occur in the sample (approximately 30 days). This is usually not a significant issue with NORM-contaminated soils since Ra-226 is typically tightly bound in the scale matrix. Radon emanation rates for NORM are often less than 5%, a characteristic observed for soil samples from the case study site. The deliverable time for sample results from off-site laboratories can range from several days, when rapid turnaround is specified, to several weeks. Slow turnaround times make it nearly impossible to use off-site laboratories for supporting ASAP data collection.

*Ex situ* analysis of soil samples by gamma spectroscopy also can be conducted on site in a mobile laboratory setting. Using a Marinelli sample geometry and count times of 15 minutes, on-site *ex situ* gamma spectroscopy can be used for relatively rapid analysis of soil samples with detection limits in the range of background levels or less for Ra-226. With proper planning, an on-site *ex situ* gamma spectroscopy system can analyze between 20 and 30 samples per day. *In situ* High Purity Germanium (HPGe) gamma spectroscopy uses basically the same detector equipment set above the ground to measure gamma flux from near surface *in situ* soils. Assuming some known distribution of contamination in soils (typically homogenous laterally and with depth), *in situ* HPGe systems can be calibrated to convert measured gamma activity to isotope-specific activity concentrations.

For *in situ* HPGe systems, the “field of view” refers to the area of soil beneath the detector that contributes the bulk of the gamma flux measured by the detector. Collimated systems use shielding to control the size of the field of view. Uncollimated systems use the height of the detector above the ground’s surface to accomplish the same task. For an uncollimated system with the detector set 1 meter above the ground, a field of view of approximately 100 square meters is produced. When an *in situ* HPGe measurement is made, the resulting isotopic concentration is assumed to represent the average concentration over the field of view of the measurement. Most NORM guidelines represent spatially averaged concentrations, i.e., 5 pCi/g averaged over 100 square meters (Table 1.1). In these cases, the results from an *in situ* HPGe measurement actually provide data that are more directly comparable with cleanup guidelines than data obtained from discrete samples. For Ra-226, reasonable detection limits can typically be obtained with a 15-minute measurement time. With the proper supporting software, *in situ* HPGe measurements yield accurate isotopic activity concentrations for Ra-226 in the field.

*In situ* HPGe systems have been used for environmental characterization for more than 20 years, primarily for emergency response to reactor accidents and to characterize the environmental impacts of weapons tests. *In situ* HPGe systems are currently commercially available from a number of vendors. Despite their long and well-established track record, they have not been widely used to support remediation work and are typically treated as a “new” or “unproven” technology by regulators. Both *ex situ* and *in situ* HPGe systems require relatively sophisticated and expensive equipment and trained personnel for correct operation. On a per measurement cost, however, on-site gamma



spectroscopy systems can typically reduce the total per sample cost of data collection and analysis by 50% when compared with off-site laboratory analyses.

HPGe gamma spectroscopy systems rely on High Purity Germanium crystals to measure gamma flux. HPGe systems typically have excellent resolution but low efficiencies. High resolution means that HPGe systems can quantify isotopic activity concentrations even when there is a mixture of isotopes present that are gamma emitters. Low efficiency means that an HPGe system needs a significant measurement time to accomplish this task. In contrast, sodium iodide-based (NaI) systems have high efficiencies but low resolution. High efficiency means that NaI-based systems obtain stable gamma counts with short measurement times. Low resolution means that these same systems have trouble discerning between isotopes when more than one isotope is present and is contributing to the total counts. For NORM sites where Ra-226 is the sole isotope of concern, lack of resolution is not an issue for NaI-based systems. Lack of resolution becomes more of an issue for these systems when other isotopes such as Ra-228 are present above background, or where background levels of other naturally occurring isotopes fluctuate significantly.

*In situ* and *ex situ* NaI-based gamma spectroscopy systems are available that provide isotopic concentrations for either discrete samples or *in situ* soils. These systems typically can produce isotopic concentration estimates with a much shorter measurement time than an HPGe system; however, the accuracy of the measurement is much more uncertain. The NORM Instruments and Services (NORM IS), Inc. RadInSoil™ meter is one example of an *in situ* system. NaI-based systems also can be used in a gross activity screening mode, where gross activity measured in counts per unit time is produced. These types of systems have a long history of use as screening tools, in which the detector is swung about 6 inches above the ground as a technician walks over a site. Traditionally, technicians have used an audible signal to monitor fluctuations in the gross activity measured. In recent years, these types of instruments have been coupled with data loggers and Global Positioning Systems (GPSs) that store the measured count rates and provide coordinates for the data. With differential correction, current GPSs can provide these locations with submeter accuracy. Typical measurement times for these types of systems are only 2 seconds. With a 2-second acquisition time, a 2 x 2 NaI system can discern elevated Ra-226 levels that are only 2 or 3 pCi/g above background (MARSSIM 1997). These types of walkover systems can produce dense, complete coverage of a site's surface at relatively little expense, typically on the order of a couple of hundred dollars per acre.

### **1.3.2 ASAP Decision Making for NORM Contamination**

The second requirement for an ASAP approach to NORM characterization and remediation is an effective methodology for making decisions about data collection in response to the information that real-time data collection systems produce. The key questions that must be answered are where should data be collected next? How much data should be gathered? When can data collection stop? When characterization is folded into the remediation of soils, additional questions are added to the list. Which soils must be treated as above the cleanup guidelines? Which are below? For which soils are

conclusions uncertain? For these uncertain soils, is additional data collection justified to clarify their level of contamination?

In most cases, the cleanup guidelines for NORM contamination are well established. These typically include some spatially averaged concentration guideline that residual contamination must satisfy (Table 1.1). MARSSIM also references “elevated area” or “hot spot” criteria that address the particular concerns associated with very localized, highly elevated areas that might otherwise satisfy the spatially averaged concentration guideline. This type of elevated area criteria is currently not found in state NORM guidelines. The most common spatially averaged concentration guideline is the 5/15 rule; i.e., surficial soils must contain less than 5 pCi/g plus background of Ra-226 averaged over some specified area, while subsurface soils (i.e., soils at depths greater than 6 inches) must contain less than 15 pCi/g plus background of Ra-226 averaged over some specified area (Table 1.1). The characterization/remediation decisions that must be made for a site, therefore, are reduced to an either/or decision. Either a particular volume of soil satisfies the appropriate guidelines or it does not. Additional decisions may have to be made for a particular soil volume, but these also are usually binary. For example, the preferred disposal option may be placement in a landfill that has a waste acceptance criterion that cannot be exceeded. The decision that must be made for a particular load of soil is whether or not it satisfies this waste acceptance criterion.

For any particular volume of soil and any specific guideline that is being applied, one’s knowledge about that particular volume of soil falls within one of three categories. Either the soil satisfies the guideline (at some specified level of confidence), does not satisfy the guideline (at some specified level of confidence), or the information available does not allow a firm decision to be made. The principal objective of data collection during characterization or remediation of a NORM-contaminated site is to “sort” the site’s soil into one of these three categories. Preferably the volume of soil in the last category would be kept to a minimum. The assumption is that, in the interest of human health protection, any soil falling in the unknown category would be treated ultimately as not satisfying the guideline.

Figure 1.4 is a schematic of how a site’s soils might be sorted into these three categories as more and more data are collected. At the outset of a data collection program, very little might be known about a site’s soils. Some might be presumed to be contaminated on the basis of visual evidence of scale, for example, while others might be presumed to be clean because of protection by an impermeable cover such as asphalt or concrete. The majority of soils, however, will likely fall into the third category, condition unknown. Data collection focuses on moving soils from this category into either the first or second. A common theme for all data collection programs is the principle of diminishing returns to data collection. As Figure 1.4 illustrates, a point will be reached at which additional data collection will result in little further clarification of the condition of a site’s soil. Fundamental to Figure 1.4 and ASAP data collection design is the idea that data collection is an

investment whose return is a reduction in the total volume of soils that have to be remediated (i.e., those known to be contaminated and those whose condition is uncertain). If the return does not outweigh the investment, there is no reason to continue collecting data.

The most effective approach to ASAP data collection usually involves a combination of data collection technologies. A suite of technologies for NORM-contaminated sites might include 100% surficial coverage with a gross gamma walkover, selective direct measurements of *in situ* concentrations, and minimal discrete sampling for QA/QC purposes. Gross gamma walkovers provide relatively inexpensive, complete real-time information about gross activity for exposed surficial surfaces. Regulatory guidelines, however, are typically expressed in concentrations, exposure levels, or radon flux. The challenge with gamma walkover data is to develop a relationship between gross activity and the probability that the prescribed guideline has been exceeded.

Discrete soil sampling or direct *in situ* measurements with instruments capable of providing isotopic concentrations allow gamma walkover data to be interpreted. Soil sample results or direct *in situ* measurements can be used to construct a relationship between gross activity and cleanup requirements. Figure 1.5 illustrates an example of such a relationship. This histogram was constructed with data for locations that had both gamma walkover information and a direct isotopic measurement. The histogram shows the percentage of samples within a particular range of gross gamma activity that yielded isotopic concentrations over the cleanup requirement. With this type of graph, two gross activity “trigger levels” can be defined: a lower trigger level below which one can be confident that cleanup guidelines are rarely exceeded, and a second upper trigger level above which one can be confident that the cleanup guidelines are always exceeded. The range of gamma activities between these two trigger levels defines activities where definitive conclusions cannot be drawn regarding the presence or absence of soils above the cleanup requirements. This relationship will be extremely dependent on the type of sensor used for the gross gamma walkover surveys and the definition of the cleanup requirements.

By using a relationship such as that contained in Figure 1.5, the surface of a site can be divided into three regions on the basis of gamma walkover data: one where gamma walkover data clearly indicate that cleanup requirements have not been exceeded, one where gamma walkover data clearly indicate that cleanup requirements have been exceeded, and the remaining area where the gamma walkover data are inconclusive. If this third area is significant, it can be targeted with additional direct measurements to clarify its Ra-226/Ra-228 concentrations. This process yields a two-dimensional footprint for contamination but provides no immediate information on the vertical extent. If an estimate of vertical extent is required before remediation or excavation decisions can be made, this also can be performed in an ASAP mode by using gross gamma screens of soil cores. While these screens are more qualitative in nature than the analysis described so far, Ra-226 detection limits with a handheld sensor are sufficiently low that distinctions can be made between impacted and nonimpacted soils. Since most NORM contamination is likely to be near surface (unless past site activities resulted in

backfilling or burial of contaminated soils), a variety of rapid and cost-effective techniques are available for retrieving near-surface soil cores.

A vertical extent of contamination is not necessary if ASAP techniques are built into the excavation/remediation process. If excavations are organized by lifts, exposed surfaces can be rewalked and redivided into regions as excavation work proceeds, with sequential lifts of contaminated soil continuing until the dig face yields soils that satisfy the cleanup requirements. Ultimately this form of excavation will yield a contaminated soil excavation footprint that is much more precise than anything that could be determined solely on the basis of subsurface soil sampling.

The ASAP process for NORM soils consists of the following steps:

1. Soil background concentrations are determined for the site for the contaminants of concern.
2. A complete gamma walkover with GPS is performed for the site.
3. On the basis of gamma walkover results, a set of locations (between 30 and 50) is selected from impacted soils. These locations are selected so that a range of isotopic activity concentrations is sampled; the center of the range is focused on the cleanup criteria.
4. These locations are either directly measured (preferred) or sampled and analyzed.
5. The resulting data and the two trigger levels are used to develop a relationship such as that shown in Figure 1.5.
6. On the basis of these trigger levels, the surficial area of the site is divided into three regions: regions that meet the requirement, regions that do not, and regions where the walkover data are inconclusive. Gamma walkover data may need to be averaged by using moving window averaging techniques to obtain results over areas comparable with cleanup requirement definitions (typically 100 square meters).
7. If significant concern exists about subsurface contamination and estimates of vertical extent need to be obtained before excavation/remediation, a combination of soil coring along with gamma screens on resulting soils can be used to qualitatively estimate the depth of impact. This vertical profiling can be performed by using direct push technologies or more traditional hand or power soil augers/split spoons.

8. If the region where the gamma walkover data are inconclusive is large, additional direct measurements/soil samples can be collected to clarify the region's actual concentrations.
9. Excavation activities are organized by lifts. Contaminated areas identified by gamma walkover data are skimmed off lift by lift. Between each lift, the exposed surface is scanned with gamma walkover/GPS, and step 6 is repeated. Excavation continues until the dig face yields results below the lower trigger level, and/or uncertain areas have been clarified as clean via direct measurement or sampling techniques. A 100 square meter area above a cleanup requirement may actually be driven by a relatively small, localized "hot spot," and selective removal of such "hot spots" may reduce the average concentration without requiring complete removal of the 100 square-meter area. Also, this process does not require a prior definition of the vertical extent of contamination.
10. Once excavation activities have ceased, final status survey data collection can be initiated if required by the regulatory agency responsible for the site.

### **1.3.3 Final Status Surveys and Site Closure**

After a site has been remediated (or if initial characterization data suggest remediation is not warranted), the regulatory agencies responsible for the site may require some form of final status or site closure data collection. In an effort to standardize the closure of sites contaminated with radionuclides, the DoD, DOE, U.S. Environmental Protection Agency, and U.S. Nuclear Regulatory Commission recently published the *Multi-Agency Radiation Survey and Site Investigation Manual*, more commonly known as MARSSIM (MARSSIM 1997). Among other things, MARSSIM contains a recommended procedure for final status data collection that is based on discrete sampling and nonparametric statistics. In MARSSIM parlance, a remediated site is divided into final status survey units that may range in size up to an acre or more. For each final status survey unit, a sampling program is developed whose results are used to determine whether the unit is in compliance with cleanup requirements. Since MARSSIM's approach to final status data collection is based on limited discrete sampling, statistics are used to make this determination, assuming some specified level of confidence. For a variety of reasons, MARSSIM recommends nonparametric statistical tests.

The data produced by a gamma walkover during an ASAP-style data collection effort at a NORM site differ in character from those presumed by MARSSIM for final status surveys. Gamma walkover data are spatially comprehensive, while MARSSIM final status data sets are limited to a small set of locations. For any given location, gamma walkover data require interpretation relative to cleanup requirements, whereas a MARSSIM sample is definitive (i.e., provides concentrations for that location). If a MARSSIM final status survey is required for a site, direct measurement techniques can be substituted for the more traditional soil sampling to complete the MARSSIM analysis. When these

direct measurement techniques include *in situ* HPGe measurements, relatively fewer measurements are required to satisfy the statistical tests for compliance determination as compared with discrete samples, because each HPGe measurement is already an area average. Whether an *in situ* HPGe system is used for final status survey work or not, the use of real-time data collection techniques allows immediate determination regarding the compliance status of a particular final status survey unit, and, consequently, allows immediate remedial actions to take place if a final status survey unit is not in compliance.

**Table 1.1 Exemption Levels Defining Regulated NORM in Existing or Proposed State-Level Regulations or Guidelines**

State	Radium Exemption Level	Radium Cleanup Standard	Regulatory Citation	Regulating Agency
Arkansas	<5 pCi/g of Ra-226 and/or Ra-228	Averaged over any 100 m <sup>2</sup> : #5 pCi/g of Ra-226 or Ra-228 above background, averaged over the first 15 cm of soil below the surface; and #15 pCi/g of Ra-226 or Ra-228 above background, averaged over 15-cm thick layers of soil more than 15 cm below the surface.	<i>Rules and Regulations for Control of Sources of Ionizing Radiation</i> , Section 7, “Naturally Occurring Radioactive Materials (NORM).”	Department of Health, Division of Radiation Control and Emergency Management
Louisiana	#5 pCi/g of Ra-226 or Ra-228 above background	Averaged over any 100 m <sup>2</sup> : #5 pCi/g of Ra-226 or Ra-228 above background averaged over the first 15 cm of soil below the surface; and #15 pCi/g of Ra-226 or Ra-228 above background, averaged over 15-cm thick layers of soil more than 15 cm below the surface; or #30 pCi/g of Ra-226 or Ra-228 averaged over the 15-cm depth increments, provided the total effective dose to members of the public does not exceed 0.1 rem/yr.	Title 33, <i>Louisiana Administrative Code</i> , Part XV, Chapter 14, “Regulation and Licensing of Naturally Occurring Radioactive Materials (NORM).”	Department of Environmental Quality, Radiation Protection Division
Michigan (see note 1)	#5 pCi/g of Ra-226 above background	Averaged over any 100 m <sup>2</sup> : #5 pCi/g of Ra-226 above background averaged over the top 15 cm of soil below the surface; and #15 pCi/g of Ra-226 above background, averaged over succeeding 15-cm thick layers of soil.	<i>Cleanup Guidelines for Radium-226 to Allow Release for Unrestricted Use</i>	Department of Environmental Quality, Drinking Water and Radiological Protection Division
Mississippi	<5 pCi/g of Ra-226 or Ra-228 above background; or <30 pCi/g of Ra-226 or Ra-228, averaged over any 100 m <sup>2</sup> , if the radon emanation rate is #20 pCi/m <sup>2</sup> /s	Averaged over any 100 m <sup>2</sup> : #30 pCi/g of Ra-226 or Ra-228 averaged over a maximum depth of 15 cm of soil below the surface if the radon emanation rate is <20 pCi/m <sup>2</sup> /s; or if the radon emanation rate is \$20 pCi/m <sup>2</sup> /s, #5 pCi/g Ra-226 or Ra-228 averaged over the first 15-cm of soil below the surface; and #15 pCi/g Ra-226 or Ra-228, averaged over 15-cm thick layers of soil more than 15-cm below the surface.	Regulations for Control of Radiation in Mississippi, Part 801, Section N, “Licensing of Naturally Occurring Radioactive Materials (NORM).”	Department of Health, Division of Radiological Health
New Mexico	#30 pCi/g Ra-226 above background	Averaged over 100 m <sup>2</sup> : #30 pCi/g Ra-226 above background in soil in 15-cm layers.	Title 20, <i>New Mexico Administrative Code</i> , Chapter 3.1.14 “Naturally Occurring Radioactive Materials (NORM) in the Oil and Gas Industry.”	Environment Department, Environmental Improvement Board

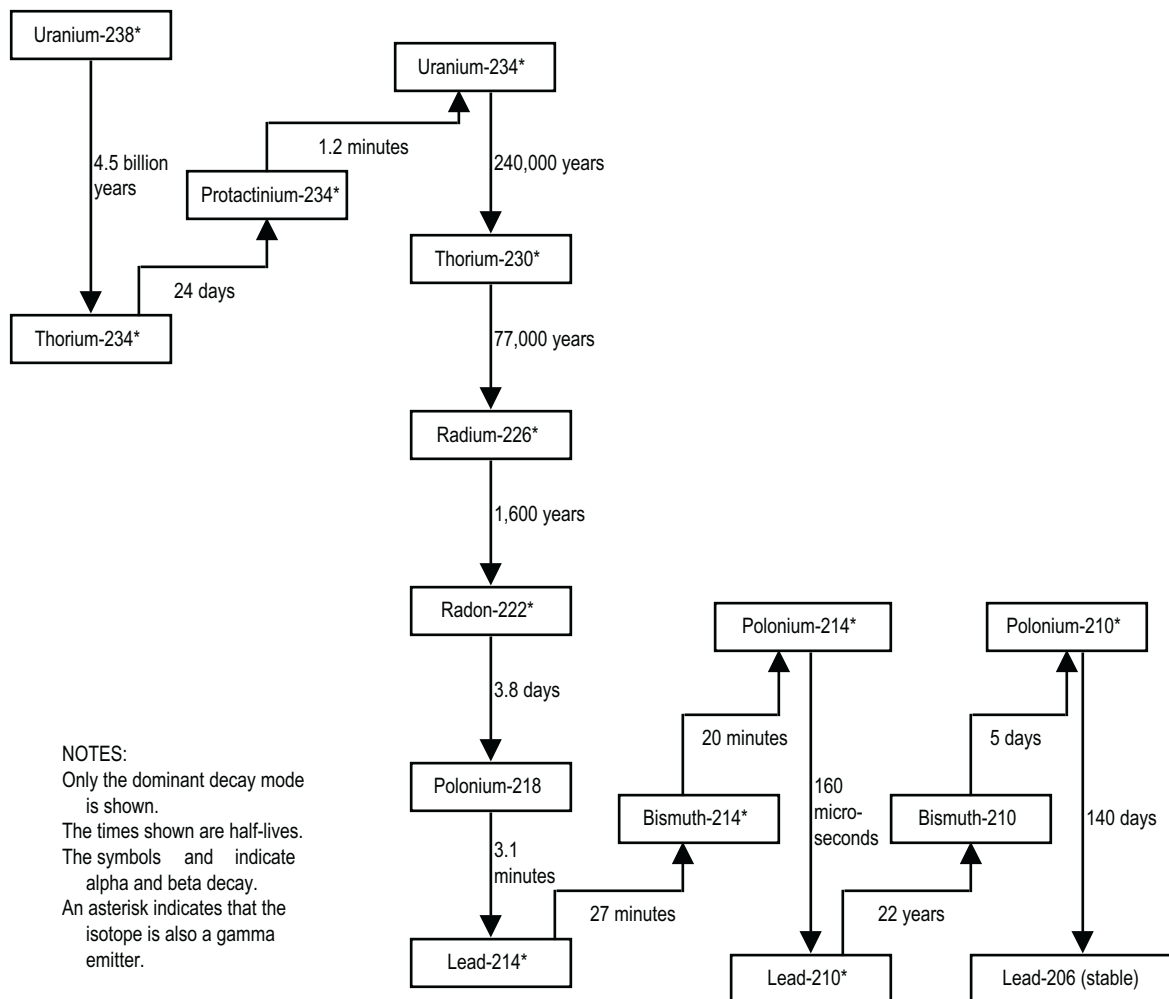
**Table 1.1 (cont.) Exemption Levels Defining Regulated NORM in Existing or Proposed State-Level Regulations or Guidelines**

State	Radium Exemption Level	Radium Cleanup Standard	Regulatory Citation	Regulating Agency
Ohio	#27 pCi/g of Ra-226 or Ra-228, if the radon emanation rate is <20 pCi/m <sup>2</sup> /s; or #5 pCi/g of Ra-226 or Ra-228 if the radon emanation rate is <sup>3</sup> 20 pCi/m <sup>2</sup> /s	Averaged over any 100 m <sup>2</sup> : #27 pCi/g of Ra-226 or Ra-228 averaged over the first 15 cm below the surface, if the radon emanation rate is <20 pCi/m <sup>2</sup> /s; or # pCi/g of Ra-226 or Ra-228 averaged over the first 15 cm below the surface, if the radon emanation rate is \$20 pCi/m <sup>2</sup> /s.	Ohio Administrative Code 3701-39-021, "Standards for Handling Radioactive Material."	Department of Health and Radiation Control
Oklahoma (proposed)	#30 pCi/g Ra-226 or Ra-228	Averaged over 100 m <sup>2</sup> : #30 pCi/g Ra-226 or Ra-228 averaged over a 15-cm layer of soil below the surface.	See note 2.	See note 2.
Texas	#30 pCi/g of Ra-226 or Ra-228	Averaged over any 100 m <sup>2</sup> : #30 pCi/g of Ra-226 or Ra-228 averaged over the first 15 cm of soil below the surface.	Title 25, Texas Administrative Code, Chapter 289, Rule 259, "Licensing of Naturally Occurring Radioactive Materials (NORM)."	Department of Health, Bureau of Radiation Control
CRCPD	<5 pCi/g of Ra-226 and Ra-228 above background	Averaged over any 100 m <sup>2</sup> : #5 pCi/g of Ra-226 and Ra-228 above background averaged over any 15-cm layer of soil below the surface.	<i>Suggested State Regulations for the Control of Radiation</i> , Part N, "Regulations and Licensing of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)."	See note 3.

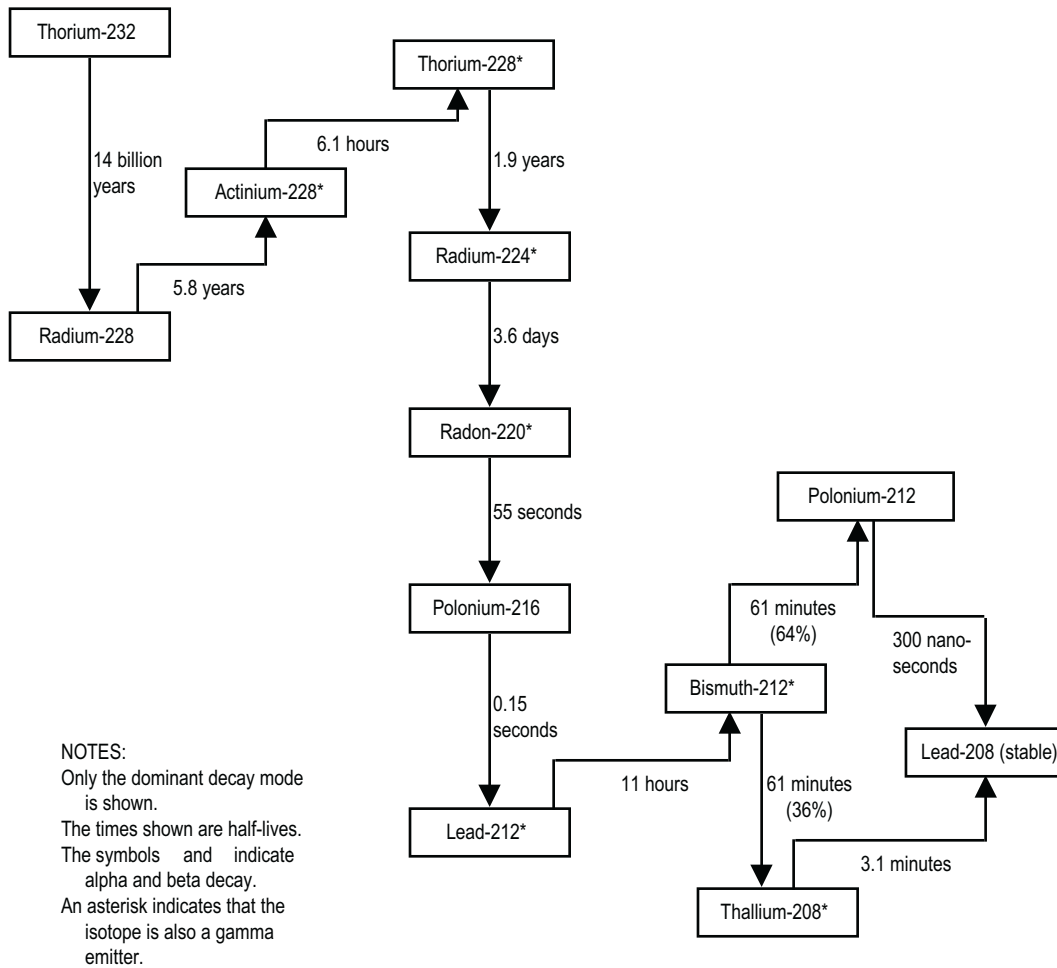
Notes:

1. Michigan has not promulgated regulations defining NORM exemption levels; it has, however, issued guidelines for cleaning up property contaminated by Ra-226.
2. In Oklahoma, the proposed rules have been drafted by the Radiation Management Advisory Council; the rules are proposed to be located in Oklahoma Regulation, Title 252, Chapter 400, Subchapter 19, "Naturally Occurring Radioactive Materials."
3. The CRCPD's regulations are intended for consideration by state agencies developing their own NORM regulations.





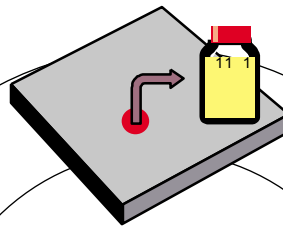
**Figure 1.1 U-238 Decay Series**



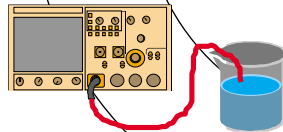
**Figure 1.2 Th-232 Decay Series**



1) Planning Phase



2) Samples Collected



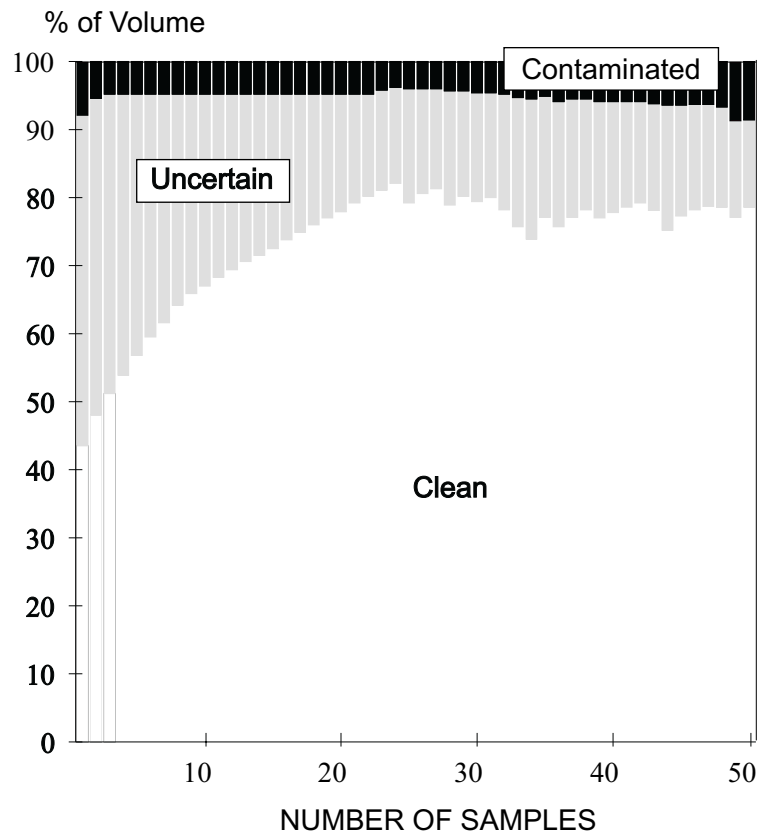
3) Samples Analyzed



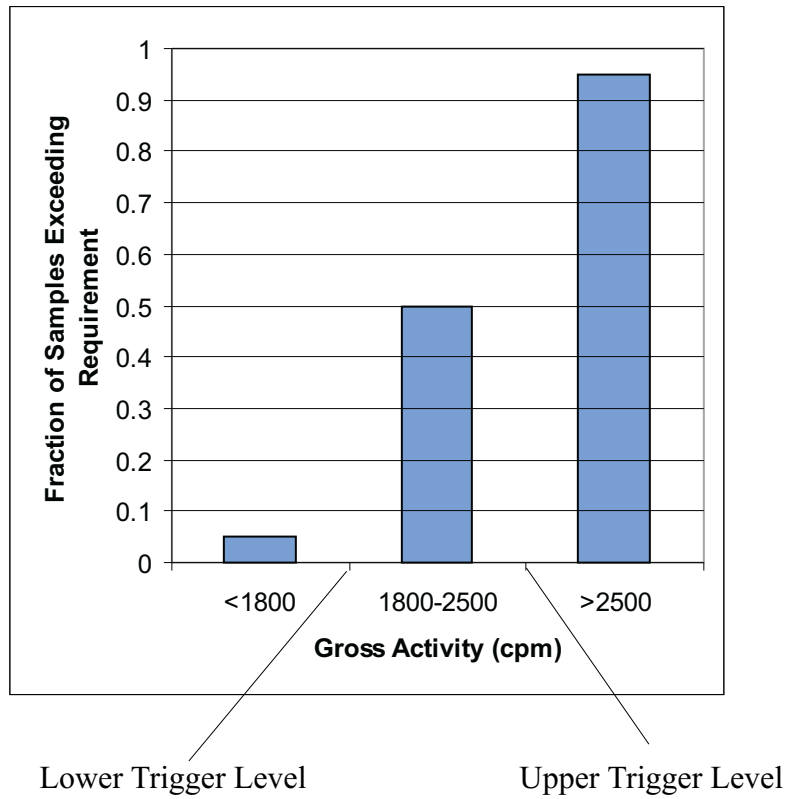
4) Decision Made

**Figure 1.3 Adaptive Sampling and Analysis Programs**

## Classification of Site Soils



**Figure 1.4 Return on Data Collection Investments**



**Figure 1.5 Relationship between Gamma Walkover Data and Cleanup Requirements**

## **2 CASE STUDY**

### **2.1 Description of Site**

The site used for the ASAP demonstration is a privately owned pipe storage yard in central Michigan. The site includes approximately 3 acres that were used for pipe storage and maintenance activities (Figures 2.1 and 2.2). Most of the storage yard is fenced. The site is bounded by a golf course on the west, a small river on the north, an office building and parking lot on the south, and another privately held industrial parcel on the east. Used piping and associated materials were stored and refurbished at the yard. In 1991, the owner conducted a site survey and ascertained that portions of the site had elevated surficial gamma activity. The owner gridded the site and selectively containerized approximately 38 cubic yards of contaminated soils that had been identified by his gamma survey. These soils were stored in 148 forty-gallon plastic drums in the northeast corner of the yard (Figure 2.3). Upon completion of this excavation work, the site was tilled, and the remaining pipe that exhibited scale with elevated Ra-226 activities was removed. In 1997, the State of Michigan Department of Environmental Quality (DEQ) performed a cursory site survey and identified additional locations on site where elevated gamma activity was present. In addition, the DEQ sampled soils from the stored drums and found Ra-226 concentrations that ranged from 1.0 up to 3,000 pCi/g.

### **2.2 Methodology**

The goals of the demonstration work at the site were (1) to demonstrate how a combination of real-time data collection technologies could be used to support ASAP characterization and precision excavation for NORM-contaminated soil; (2) to establish performance and cost parameters for the technologies demonstrated; and (3) to meet the data collection needs of the site owner. The owner of the site had two very specific needs: to bring *in situ* soils into compliance with DEQ cleanup standards by selectively identifying and excavating contaminated soils that remained at the site and to acquire sufficient characterization information about the stored soils to allow for their disposition off site. The DEQ guidance establishes a cleanup goal of 5 pCi/g above background for Ra-226 (Table 1.1). The DEQ also has an established policy of allowing NORM-contaminated soils to be disposed of in nonhazardous municipal landfills providing certain conditions are met (DEQ 1996). These conditions include a requirement that the average concentration for each load of soil be less than 50 pCi/g, and that individual representative samples from the soils should not exceed Ra-226 concentrations of 100 pCi/g.

#### **2.2.1 ASAP Characterization and Precision Excavation**

##### **2.2.1.1 Site Technologies**

The ASAP characterization and precision excavation work were based on three real-time direct measurement technologies: mobile gross gamma surveys combined with a GPS (Figure 2.4), *in*

*situ* gamma spectroscopy using an HPGe system (Figure 2.5), and *in situ* measurements with a NaI-based instrument called RadInSoil that was developed by NORM IS, Inc. (Figure 2.6). A general description of each technology can be found in Section 1.3.1. A limited number of discrete samples were collected and analyzed off site by Argonne's Analytical Chemistry Laboratory (ACL) using gamma spectroscopy and by the State of Michigan's DEQ. Finally, a limited number of soil samples were collected and analyzed using Marinelli containers and HPGe gamma spectroscopy systems on site. *Ex situ* samples were not allowed a 30-day progeny ingrowth time, since it was assumed that radon emanation was not significant for contaminated soils at this site. This assumption was substantiated with radon emanation measurements.

The mobile gross gamma surveys used a system known as a miniFIDLER (Field Instrument for Detecting Low Energy Radiation). MiniFIDLER systems make use of thin, wide-window NaI crystals. MiniFIDLER systems are optimized for recording low-energy gamma emissions. In the case of Ra-226 and its progeny, a standard 2 x 2 NaI system would have had greater counting efficiencies. However, a 2 x 2 NaI system was not available for the fieldwork, and as the data demonstrated, the miniFIDLER systems provided satisfactory performance. These instruments were shielded to lessen the effects of "shine" from sources other than soils directly below the crystal. This was an issue at the demonstration site because of drummed NORM-contaminated material stored on site. The miniFIDLER was combined with a Trimble GPS (Figure 2.4).

The typical protocol for gamma surveying was to walk parallel lines separated by approximately 5 feet, with 2-second data acquisition times. At a normal survey pace, this acquisition time produced a reading separation of approximately 3 feet. Each data reading produced a gross count value and a location stamp. When areas with elevated readings were encountered, the operator would stop and further investigate the immediate area. All data were electronically recorded using the GPS data logger. Upon completion of a particular survey, the data were downloaded, color coded by activity, and mapped with a Geographical Information System (GIS) package. For *in situ* soils, gamma surveys were conducted before excavation work for the entire site. Upon the completion of excavation work, excavated areas were surveyed again. The resulting data sets were pooled into two master copies, a preexcavation data set and a postexcavation data set.

The miniFIDLER systems were used for a number of purposes: (1) to provide maps showing the general spatial patterns of surficial contamination for the site; (2) to develop relationships between cleanup criteria and gross gamma activity levels; (3) to identify areas with highly elevated activities ("hot spots"); (4) to delineate areas requiring excavation either because of general elevated levels of activity or because of the presence of hot spots; and (5) to indicate when sufficient *in situ* soil had been removed to satisfy cleanup criteria. In addition, the miniFIDLER systems were used to screen soils that were removed from drum storage.

*In situ* gamma spectroscopy makes use of HPGe-based systems. *In situ* gamma spectroscopy provides accurate measurements of isotopic activity concentrations in near-surface soils. Both

collimated and uncollimated systems were used at the site. The collimated system was calibrated for the pan geometries (Figure 2.7) used to characterize soils contained in the drums. The uncollimated system was used for surficial *in situ* soils (Figure 2.5). The uncollimated system was set at a height of approximately 1 meter off the ground and yielded a field of view of approximately 100 square meters. In all cases, read times of approximately 15 minutes were used for direct measurements. The *in situ* HPGe systems were used to (1) quantify the average concentration of soils contained in the drums; (2) quantify the average concentration present for elevated areas identified by the gamma surveys; (3) verify that excavation work in elevated areas reduced concentrations to acceptable levels; and (4) provide limited average concentration data in support of final status surveys.

The RadInSoil instrument is a direct measurement system for Ra-226 based on an NaI crystal (Figure 2.6). The RadInSoil provides equivalent Ra-226 activity concentration estimates for soils directly beneath the instrument's viewing window. Read times for the instrument range from 5 to 10 minutes. The RadInSoil instrument was used for a number of different purposes: (1) to establish the relationship between gamma survey results and cleanup guidelines; (2) to quantify the concentration of Ra-226 associated with "hot spots"; and (3) to conduct data collection in support of final status surveys.

Discrete samples were collected from the background locations, from selected hot spots, from most of the pans, and from selected final status survey unit locations. Discrete samples were analyzed with one or more methods, including on-site gamma spectroscopy using a Marinelli geometry, off-site gamma spectroscopy at ANL's ACL, and off-site gamma spectroscopy at the Michigan DEQ. Discrete samples were used for several purposes: (1) determination of background concentrations for several key gamma-emitting isotopes; (2) establishment of radon retention percentages for background soils and for scale-contaminated soils; and (3) verification of *in situ* measurement results obtained from the *in situ* HPGe systems and the RadInSoil instrument.

#### **2.2.1.2 *In Situ* Soil Characterization and Excavation**

The characterization and excavation of *in situ* soils using ASAP and precision excavation techniques were performed using the following steps:

1. Background concentrations for key isotopes were determined by analyzing soil samples from seven locations around the site. Each of these locations was initially scanned for gross gamma activity to ensure that they were, in fact, unlikely to have Ra-226 concentrations above background. This information was required because cleanup guidelines for the site are posed in terms of pCi/g, in addition to background, and it was needed for calibrating the RadInSoil instrument.
2. A complete gamma walkover survey was conducted over the site using the combined miniFIDLER/GPS. This walkover was conducted using 2-second acquisition times, a



walking speed of approximately 1.6 feet/second, and a line spacing of approximately 5 feet. This resulted in approximately 5,800 discrete data points per acre. While the data were recorded electronically in a data logger, the operator was also monitoring the activity recorded by the meter. Where higher levels of activity were observed, the operator would more carefully walk the immediate surroundings, thus providing a greater density of points for those areas. Areas with high gross activity readings were flagged, and the flagged positions were numbered.

3. RadInSoil measurements were taken at more than 40 of the flagged elevated areas to assist in developing the relationship between gross activity readings and Ra-226 concentrations. Early in the course of the data collection, it was observed that many of these locations were highly localized, i.e., even moving a foot or two off from the center of the hot spot brought activities back to near background. Because of this observation, each point was carefully screened using a miniFIDLER before RadInSoil data collection so that the instrument was centered over the highest activity level. In addition to the RadInSoil Ra-226 concentration, the static miniFIDLER value was recorded. These data were used to determine miniFIDLER readings that posed potential Ra-226 concerns.
4. *In situ* HPGe measurements were taken over broader areas of elevated miniFIDLER readings to determine whether, on average, these areas exceeded 5 pCi/g.
5. Areas were scraped with a front-end loader where either the HPGe or miniFIDLER data indicated Ra-226 concentrations of concern. Upon completion of scraping, the area was rewalked with the miniFIDLER to confirm that contamination had been removed. For larger areas, confirmatory HPGe measurements were also taken.
6. The last step in this process consisted of final status surveys. The site was divided into final status survey units. A fixed number of discrete sampling locations were allocated to each survey unit based on a MARSSIM style analysis. The Ra-226 concentrations were measured for these locations with the RadInSoil instrument, and the results from these measurements were used to determine whether the final status survey unit complied with spatially averaged Ra-226 guidelines. The final postexcavation gamma walkover data sets were reviewed to determine the maximum localized Ra-226 concentration observed in surficial soils after excavation.

#### **2.2.1.3 Drummed Material Characterization**

The drummed material at the site posed the greatest characterization challenge. The drummed soil characterization work had two objectives: (1) estimation of the average concentration of soils

contained in each drum to allow for their proper disposition; and (2) identification of and segregation of soils that were likely to exceed 100 pCi/g.

The approach was to construct a pair of metal “pans,” i.e., rectangular steel containers with low walls into which drummed soil could be dumped for characterization. Each pan was capable of holding the contents of four to six drums. The exterior surfaces of the drums were screened with a miniFIDLER, and the drums were organized by general levels of discernable external gamma activity. The intent was to avoid mixing in the pans soils from drums with relatively low activities with soils from drums with relatively high activities. Once organized, the drums were dumped into the pans. After each pan was “full,” i.e., contained a soil layer approximately six inches in depth, the pan was measured with an *in situ* HPGe instrument using count times of approximately 20 minutes. Figure 2.7 shows one of the two pans filled with soil; the *in situ* collimated HPGe system is suspended above the pan. The HPGe instrument used was calibrated for the geometry of the pans and centered at a height of 1 meter above each pan when a measurement was made. In addition, five sampling locations were identified in each pan (one in the center and one from the center of each quadrant). For some pans, each location was individually sampled and/or measured using the RadInSoil instrument. For the balance of the pans, a composite was formed from the sampled soils and was analyzed using a Marinelli geometry with gamma spectroscopy. Figure 2.8 shows RadInSoil data collection for a pan, along with a resulting composite sample. In most cases, the State of Michigan analyzed the composite for Ra-226. In some cases, the composite sample was split; split analyses were conducted by the State of Michigan and by ANL’s ACL. Finally, the soils were also screened *in situ* using the miniFIDLERs to determine if any highly elevated soils could be identified for segregation.

On the basis of the HPGe results, the panned soils were segregated into one of four bins for bulk storage (Figure 2.9). The first bin was reserved for soils greater than 5 pCi/g but less than 30 pCi/g. The second bin was intended for soils greater than 30 pCi/g but less than 50 pCi/g. The third bin contained soils greater than 50 pCi/g but less than 100 pCi/g. The fourth bin received all soils greater than 100 pCi/g.

### **2.2.2 Technology Performance**

Of the three principal technologies that were part of the demonstration, the *in situ* HPGe and gamma walkover surveys have been successfully used in the past at DOE and DoD sites for Ra-226 characterization purposes. Both have a well-established performance record for Ra-226. The RadInSoil instrument, however, is a relative new technology specifically designed for Ra-226 characterization. Consequently, technology performance evaluation activities focused on its performance, which can be measured in a variety of ways. The demonstration focused on three: accuracy, precision, and cost. Accuracy was addressed by collecting samples from locations measured by the RadInSoil instrument, analyzing these samples in the laboratory, and comparing their results with those from the RadInSoil instrument. Precision was addressed by selecting two locations at the site (one near background levels and one with elevated Ra-226 concentrations) and taking repeated

measurements at these locations using various measurement times. This approach provided information about how precision behaved for different Ra-226 concentrations, and it allowed an evaluation of how precision changed with changing measurement times. Finally, cost was determined by observing measurement throughput and using this throughput information to develop cost-per-measurement estimates.

## **2.3 Results**

### **2.3.1 *In Situ* Soil Characterization and Precision Excavation**

#### **2.3.1.1 Background Information for the Site**

An initial set of seven samples was collected for background purposes from the immediate vicinity of the site. Figure 2.10 shows the sample locations. Each location was first screened for gross activity to ensure that there was no obvious indication of contamination. Each sample was analyzed via gamma spectroscopy by ANL's ACL and was then bagged and reanalyzed after a 30-day ingrowth period to determine percent radon retention. The initial results for Ra-226 showed a range from 0.31 to 0.62 pCi/g, with an average of 0.48 pCi/g. For the same locations, the range of concentrations observed with the RadInSoil instrument was from 0.27 to 0.65 pCi/g, with an average of 0.48 pCi/g. The DEQ analyzed splits from five of these locations. For the four with detectable levels of Ra-226, DEQ results ranged from 0.6 to 1.0 pCi/g, with an average of 0.8 pCi/g. The DEQ results, however, had counting errors on the order of 0.5 pCi/g. One *in situ* HPGe measurement was taken at location BG04, resulting in 0.3 pCi/g. Because the background soil sample analysis indicated low background concentrations of Ra-226 relative to the various concentrations that pose regulatory concerns, all further analyses did not include the presence of background in the calculations (i.e., 5 pCi/g was assumed to be an absolute criterion). This approach allowed for a simpler and more conservative approach to characterization and remediation.

Background levels of gamma gross activity measured by the gamma survey system ranged from approximately 200 up to 1,000 counts per minute (cpm), with an average of 650 cpm. The bulk of the data fell between 500 and 800 cpm.

#### **2.3.1.2 Relationship between Gross Activity and Isotopic Concentrations**

The initial walkover for the site encountered numerous locations where gross activity was clearly elevated above background. In many cases, these occurrences were very localized. In a few instances, there were broader areas with elevated gross activity levels. Elevated locations were flagged, and for 49 of these, RadInSoil measurements were taken to determine the relationship between gross activity as measured by the miniFIDLER system and Ra-226 isotopic activity concentrations. In each of these cases, a static miniFIDLER reading was taken in addition to the RadInSoil measurement. For these locations, measured concentrations ranged from 0.6 to more than 900 pCi/g. Figure 2.11 shows a

scatter plot for the resulting data that compares gross activity with measured concentrations. The Pearson correlation coefficient for this data set was 0.98, which indicates a high degree of linear correlation between gross activity and Ra-226 concentrations. This strong relationship is not surprising given the fact that Ra-226 and its progeny are the only gamma-emitting isotopes found at the site above background levels.

There are several key concentration levels for Ra-226. At 5 pCi/g (above background) averaged over 100 square meters, Ra-226 exceeds State of Michigan guidelines for surface soils. At 15 pCi/g (above background) averaged over 100 square meters, Ra-226 exceeds State of Michigan guidelines for subsurface soils. The State of Michigan will accept soils contaminated with Ra-226 in nonhazardous municipal landfills if average concentrations are below 50 pCi/g, and if representative samples are below 100 pCi/g. On the basis of these various criteria, trigger levels were derived using the miniFIDLER/RadInSoil hot spot data set. Table 2.1 contains the results of these analyses. For each criterion, two trigger levels were defined. The lower trigger level establishes the miniFIDLER cpm below which one can be confident that the criterion is not exceeded. The upper trigger level establishes the miniFIDLER cpm above which one can be almost certain that the criterion will be exceeded. For any given criterion, the cpm range between the lower and upper trigger defines an uncertain zone. MiniFIDLER cpm values falling in this range provide inconclusive evidence of Ra-226 concentrations above or below the particular criterion.

#### **2.3.1.3 Delineation of Ra-226 Contamination Exceeding Guidelines**

Figure 2.12 shows the preexcavation walkover data color coded on the basis of the trigger levels derived in Section 2.3.1.2. The maximum *in situ* gross activity observed was almost 100,000 cpm. Figure 2.12 is particularly useful for identifying small areas of highly elevated concentrations. Figure 2.12 clearly shows that there are areas sprinkled across the site that have been impacted by NORM contamination. In several isolated cases, these impacts have resulted in highly elevated gross gamma activity, although these “hot spots” had very limited areal extent. Figure 2.13 shows the preexcavation gamma walkover data color coded with a presumed cleanup goal of 5 pCi/g. In Figure 2.13, green areas are areas where the gamma walkover data are below 1,800 cpm (i.e., there is little possibility that Ra-226 concentrations exceed 5 pCi/g). Red areas are areas where the gamma walkover data are above 2,500 cpm (i.e., Ra-226 levels likely exceed 5 pCi/g). Yellow areas are areas where the gamma walkover data are between the lower trigger level (1,800 cpm) and the upper trigger level (2,500 cpm). Figure 2.14 shows the same data averaged over 100-square-meter areas using a moving window averaging technique. This approach yields data whose physical basis is more directly comparable with the spatially averaged definition of the cleanup guidelines.

The gross gamma walkover covered an area equal to approximately 17,000 square yards (3.5 acres). On the basis of the results of the preexcavation walkover, approximately 12.9% of this area (2,200 square yards) was impacted by NORM above background levels. Approximately 3.7% of this area (630 square yards) likely exceeded 5 pCi/g. In Figure 2.14, five distinct areas emerge that have

NORM contamination at levels that likely exceed State of Michigan surficial soil guidelines: one in the northwest corner of the site, one in the northeast where the drums were stored, one in the central west portion of the site, one in the central east portion of the site and one directly south of the fence line. *In situ* HPGe measurements were obtained over the elevated area in the northwest corner of the site and over the area south of the fence. Ra-226 concentrations ranged from 4.9 to 6.3 pCi/g. On the basis of spatial averaging of the walkover data, these 5 areas cover an area of approximately 900 square yards. If these areas were excavated to 6 inches, they would have yielded a total of 150 cubic yards of soil. The fact that the above-5-pCi/g area increased with spatial averaging indicates that using precise excavation techniques that target more elevated areas would likely reduce the overall volume of soil that would require excavation and bring the site into compliance with State of Michigan guidelines.

On the basis of these data, five areas were scraped using a front-end loader. In addition, isolated elevated areas were pursued using shovels. In all, approximately 9 cubic yards of additional *in situ* soils were removed from the site. These soils were measured for average Ra-226 contamination levels in the pans. On average, these soils contained a Ra-226 concentration equal to 18 pCi/g. After scraping was complete, the scraped areas were rewalked with the miniFIDLER. Figure 2.15 shows the surface activity of the site after excavation work was conducted; again, data were color coded using the trigger levels derived in Section 2.3.1.2. Figure 2.16 shows the same data but color coded presuming a cleanup goal of 5 pCi/g. Finally, Figure 2.17 shows these same data spatially averaged using moving window techniques and a 100-square-meter averaging area. In addition, confirmatory *in situ* HPGe shots were taken at heights of 1 meter over the larger scraped areas. Table 2.2 summarizes the pre- and postexcavation *in situ* HPGe results for the five areas. The goal of the additional excavation work was not to reduce residual Ra-226 concentrations to background levels, nor was it to reduce every location to below 5 pCi/g; rather it was to bring the site into compliance with the 5 pCi/g-averaged-over-100-square-meters guideline.

In the postexcavation gamma walkover data sets, approximately 12.4% (2,100 square yards) of the site was impacted by NORM above background. Approximately 1.2% (210 square yards) remained above 5 pCi/g. However, when one spatially averages the data using moving window averages and an averaging area of 100 square meters, none of the locations are above the 5-pCi/g guidelines. This is consistent with the postexcavation *in situ* HPGe results contained in Table 2.2. The maximum *in situ* gross activity observed was 51,000 cpm along the southern fence line. However, subsequent searching for this spot failed to recover the location, which suggested that this was an instrument anomaly. Neglecting this 51,000-cpm reading, the next highest cpm reading in the postexcavation data set was 16,000 cpm, which suggests a maximum postexcavation *in situ* concentration between 30 and 50 pCi/g.

#### 2.3.1.4 Final Status Survey

To confirm that the site satisfied the 5-pCi/g guidelines, a final status survey was performed. The site was divided into 8 final status survey units, all approximately the same size (2,300 square yards). Nine locations were measured using the RadInSoil instrument for each final status survey. Figure 2.18 shows the layout of the final status survey units and the locations of the measurement points color coded by the observed Ra-226 concentration. MARSSIM's approach to final status survey data analysis is to require that the average concentration derived from the measured or sampled locations be less than the derived concentration guideline (in this case, 5 pCi/g), and that the probability that the median value is less than 0.5 be based on a nonparametric statistical test that can be established with some predefined level of certainty. For this demonstration, a certainty level of 95% was assumed. Given this certainty level and 9 sampling points, each survey unit could tolerate up to one sample exceeding 5 pCi/g and still pass the test.

Figures 2.19 through 2.26 show the results of the final status surveys for each final status survey unit, including the locations of sampled points color coded by RadInSoil-measured Ra-226 concentrations superimposed on the postexcavation gamma walkover results. Table 2.3 summarizes the results for each of the eight final status survey units, including the RadInSoil data, any corresponding ANL ACL sample results, and *in situ* HPGe results for units where HPGe data were collected. Average Ra-226 concentrations for all of the final status survey units were well below 5 pCi/g. Two final status survey units each yielded one sample above 5 pCi/g. The rest of the samples analyzed/measured were below 5 pCi/g. For the two units that did yield a sample above the criterion, both passed the nonparametric statistical test. Results for the maximum gross activity concentrations observed indicated that the maximum residual level of Ra-226 surficial contamination remaining on the site was less than 50 pCi/g.

An interesting side note is that the fraction of RadInSoil final status survey measurements that exceeded 5 pCi/g (2 out of 72 or 2.7%) was approximately the same fraction as identified by the gamma walkover surveys. This is further evidence of the effectiveness of gamma walkover surveys for NORM-contaminated sites in separating soils above guidelines from soils below guidelines.

The *in situ* HPGe measurements provide an alternative means of evaluating final status survey compliance. With a field of view of approximately 100 square meters, results from an *in situ* HPGe provide a direct point of comparison with cleanup guidelines, which are based on 100-square-meter spatial averages. This field of view represents approximately 5% of the size of the average final status survey unit at the site. Using a nonparametric statistical test but assuming sampling without replacement from a finite population (i.e., 20 HPGe measurements would constitute a complete final status survey unit), four nonoverlapping HPGe measurements that all yield results less than 5 pCi/g are sufficient for establishing at the 95% confidence level that the majority of the area in a final status survey unit is less than 5 pCi/g. This approach was demonstrated for two of the final status survey units, units 1 and 6 (Table 2.3). Given the relatively large field of view of the *in situ* HPGe measurements at the site, the

gamma walkover data suggest that at postexcavation, no HPGe measurement would encounter a 100-square-meter area above the guideline. In fact, no postexcavation HPGe measurement encountered Ra-226 above 5 pCi/g.

### **2.3.2 Drummed Soil Characterization**

One hundred forty eight plastic drums of contaminated soil were originally stored on site. Many of these drums were in very poor condition; some had significant cracks, while a few had actually burst. Many of the drums had markings on the side that gave some indication of the level of activity that they contained, although the activity units were not clear. Before being emptied and characterized in pans, the drums were sorted by general level of observed activity so that drums with similar activity levels would be mixed in the same pan. Table 2.4 identifies the drums, lists their original activity labels and their observed activity during sorting, identifies the pans into which they were dumped, and describes their condition. In all, approximately 38 cubic yards of soil were contained in the 148 plastic drums.

Each pan was characterized using a variety of techniques described in Section 2.2.1.3. Table 2.5 describes the results obtained for each pan. Average Ra-226 concentrations from the drums observed in the pans using the HPGe ranged from 14 up to 1,500 pCi/g, with an overall average of 129 pCi/g. On the basis of the observed average pan Ra-226 concentrations, the contents of each pan were placed in one of the bulk storage bins. While attempts were made to screen the pan contents *in situ* using a miniFIDLER system, the efforts were not successful. As Table 2.5 indicates, a fairly large spread of concentrations was observed in the pans from which individual samples were collected and analyzed. In general, there was excellent agreement among the various methods when estimating the average Ra-226 concentration values for individual pans. Because of the nature of NORM contamination at the site, the observed isolated nature of “hot spots” *in situ*, and the likely mixing that went on in the original excavation work, *in situ* segregation of highly elevated soils would have been a much more effective means of isolating high Ra-226 concentrations.

Table 2.6 summarizes the volumes and average Ra-226 concentrations present in the bulk storage bins when the work was completed. Two pans worth of soils were segregated into drums separate from the bins because of special concerns. Pan 27 contained soils with exceptionally high Ra-226 concentrations. Pan 28 contained soils that were mixed with an oily residue. The soils summarized in Table 2.6 include both the 38 cubic yards of soil containerized on site and the additional 9 cubic yards of soil that was removed from the site during the course of the demonstration.

### **2.3.3 Technology Performance**

Technology performance for the RadInSoil instrument addressed three critical parameters: accuracy, precision, and cost. Accuracy was measured by comparing RadInSoil measurements with 50 soil samples collected from measured locations and analyzed by the State of Michigan. Table 2.7 provides these data. Figure 2.27 shows a scatter plot that graphs RadInSoil results against State of

Michigan soil sample results for samples/measurements with concentrations less than 600 pCi/g. Table 2.8 and Figure 2.28 provide similar comparisons between 23 DEQ sample results and splits analyzed by the ACL. Figure 2.28 includes split samples with concentrations less than 150 pCi/g. Two key observations emerge from these comparisons. First, while there clearly is a strong correlation between the results measured by the RadInSoil instrument and the sample results from the DEQ, there also is considerable scatter. However, comparisons between DEQ and ACL splits showed exactly the same behavior. In fact, the correlation between the RadInSoil results and DEQ data was 0.82; in contrast, the correlation between DEQ and ACL splits was only 0.31. Eliminating two pairs with the greatest percent differences raised this to 0.53. However, the results suggest that in terms of accuracy, the RadInSoil showed at least as consistent results compared with laboratory results as the interlaboratory comparisons of sample splits. Second, the percent differences observed between the RadInSoil data and the DEQ results decrease with increasing concentrations up to about 50 pCi/g, at which point they begin increasing again.

A likely explanation for both observations is the nature of NORM contamination found at the site. NORM contamination is associated with scale. Pieces of scale themselves can have Ra-226 concentrations measured in thousands of pCi/g. The results obtained from both direct measurements and discrete sample analyses are driven by the presence or absence of scale. A sample split can yield dramatically different results if a discrete piece of scale ends up in one split and not the other. Moving a direct measurement over slightly can change the measured results significantly, depending on whether a large piece of scale is beneath the instrument or off to one side. This is especially true with a shielded instrument such as the RadInSoil. This effect was observed on a number of occasions at the demonstration site. The performance of the RadInSoil instrument from an accuracy perspective seemed within the range of what one would expect from *ex situ* analytical techniques for the type of contamination present at the site. No bias was observed, and relative differences were comparable with those observed in sample splits and cross-lab comparisons.

The RadInSoil meter assumes that Ra-226 and its progeny are the only gamma-emitting isotopes above background levels. If this assumption is violated, RadInSoil measurements will no longer accurately reflect *in situ* Ra-226 concentrations. In this case, however, the RadInSoil measurement will be conservative, i.e., it will produce Ra-226 concentration estimates that overestimate the actual Ra-226 concentrations present. Consequently, the RadInSoil measurement can still be effectively used for determining which areas are below established criteria for Ra-226. In addition, if a consistent ratio is observed between Ra-226 and Ra-228, the RadInSoil measurements can be adjusted to reflect this ratio.

The precision of the RadInSoil measurement was evaluated by using two established *in situ* measurement locations on site; multiple measurements were conducted at both locations using different measurement times. These two locations were BG04, with a Ra-226 concentration near background, and H11, with a Ra-226 concentration slightly above the 5-pCi/g guidance level. At BG04, 11 readings were collected over 2 days by using a 600-second count time. Fourteen



300-second count time measurements also were collected over the space of 5 days. At H11, 22 measurements with a 300-second count time were collected over 7 days. Another 11 measurements with a 120-second count time were collected over the course of 1 day. Table 2.9 summarizes these data and provides the observed mean, standard deviation associated with the raw measurements, and standard deviation associated with the means.

Several conclusions can be drawn from these data. First, for both locations the average values observed for the different count times were within the standard errors associated with the average values, which indicates that no evidence exists of measured values being a function of count time. Second, counting statistics seemed to be the predominant contributor to observed standard deviations for BG04. Where counting statistics predominate, one expects standard deviations to be related to the inverse square root of count times. For example, increasing the count time by a factor of four should decrease the observed standard deviation of measurements by a factor of 2. For BG04, as count times double the standard deviation of the data decreases by approximately the inverse of the square root of two. The relationship between count time and standard deviation for H11 is not as strong, perhaps in part because of the relatively short count times used at H11 (only 120 seconds). At such short measurement times other sources of error may predominate, which may explain the fact that increasing measurement times reduce standard deviations, but not to the extent one would expect if the original error was attributable to counting statistics alone. Third, while absolute standard deviations grow with increasing concentrations, the relative error shrinks for the RadInSoil. And fourth, the standard deviations observed for a 300-second measurement reading at background Ra-226 are approximately one-third of background concentrations and drop to one quarter for 600-second measurements. For discerning whether a location is above or below 5 pCi/g, even a measurement time as short as 120 seconds appears to give satisfactory standard deviations, i.e., standard deviations that are less than 10% of the clean-up guideline.

The last performance criterion evaluated for the RadInSoil was cost of implementation. Assuming five minutes for completing a measurement and recording its results and five minutes for moving the instrument and setup (setup is minimal), measurement production rates can reach as high as six readings per hour. Total per-measurement expenses include the amortized capital cost associated with purchasing the instrument/or rental costs and the cost of operation. Operational costs are largely captured by the cost of manning the instrument. The instrument requires only one person to operate, and the technical training required to operate the instrument once effectively calibrated is minimal. Assuming a measurement throughput rate of 6 measurements per hour, per-measurement costs would likely range between \$5 and \$15. This compares very favorably with *in situ* HPGe measurements, which are typically on the order of \$100 per measurement, and *ex situ* gamma spectrometry results, which are around \$200 per sample when sample collection/transportation costs are included.

## 2.4 Overall Performance of ASAP Approach to NORM Data Collection

The use of ASAP techniques for data collection at NORM-contaminated sites has several distinct benefits over more traditional approaches that emphasize reliance on discrete sample collection. In general these include reduced per sample data collection costs, a reduction in the number of discrete samples collected, a more precise definition of contamination footprints, a better documented characterization/remediation effort, and tightened schedules. The Michigan case study demonstrated all of these benefits.

### *Reduction in Per-Sample Data Collection Costs*

The technologies fielded by the demonstration on a per unit of information basis compared very favorably with traditional soil sample collection and analysis from a cost and data quality perspective. Current costs for soil sample collection and *ex situ* gamma spectroscopy analysis are on the order of \$200 per sample. Each sample yields information about Ra-226 contaminant concentrations for one location. In contrast, per-location information costs for the gamma walkover survey were on the order of \$0.10 per reading (approximately 5,000 readings per acre and approximately \$500 per acre for a gamma walkover). Although the gamma walkover results were not directly equivalent to isotopic concentrations derived from soil samples, as the Michigan work demonstrated, there was an excellent correlation between gamma walkover data and Ra-226 concentrations. Per-measurement costs for the RadInSoil instrument were on the order of \$10, with resulting data that compared very favorably in terms of accuracy and precision with *ex situ* gamma spectroscopy for Ra-226. Per-measurement costs for the *in situ* HPGe were on the order of \$100 per measurement. Data quality was almost equivalent to *ex situ* gamma spectroscopy, and data results were more directly comparable with the definition of cleanup requirements than discrete sample results.

### *Reduction in Number of Discrete Samples Collected*

The Michigan fieldwork demonstrated how characterization activities for NORM could almost eliminate discrete sampling and its high associated costs from data collection programs. For the Michigan site, discrete samples were used to establish background and as QA/QC checks on the real-time results. The number of QA/QC samples collected was no greater than the number that would have been collected to serve the same function for a data collection program based solely on discrete samples. A relatively large number of samples were also collected and analyzed by the State of Michigan. These were used to verify the accuracy of the RadInSoil instrument and also were used by the state as verification data for the drum characterization work and final status survey work. However, these samples did not provide any additional information from a site characterization perspective that had not already been obtained by real-time data collection.

### *Precision of Excavation Footprints/Accuracy of Characterization Conclusions*

The use of real-time data collection technologies in an ASAP framework not only reduces the cost of collecting information, it also results in a better characterization/remediation product. Better here is defined as more accurate delineation of the footprint of soils exceeding cleanup requirements. In the case of NORM, this product is the complete coverage obtained for a site using gamma walkover/GPS, along with the ability to select supplemental direct measurement locations in the field to verify or clarify gamma walkover results, and then to respond to those direct measurement results. This capability is particularly important for sites where contamination is likely to be highly localized, scattered, and spotty, as compared with contamination that might result from a spill event in which a fairly well-defined plume might be produced.

The Michigan demonstration site was an excellent example of spotty contamination. The walkovers at the site revealed NORM contamination scattered at more than 100 specific locations across the facility. Additional analysis of the walkover data sets using the relationships contained in Table 2.1, however, identified only 5 distinct areas where soils would exceed 5 pCi/g over a 100-square-meter area. Selectively scraping the hottest portions of these five elevated areas brought each of the areas back into compliance with State of Michigan guidelines. Subsequent gamma walkovers verified that compliance was achieved, as did ultimately the final status survey work. In contrast, the soil removed averaged 18 pCi/g, on the basis of *in situ* HPGe measurements using the soil pans.

Reliance on discrete preplanned soil sampling alone would only have identified a handful of the locations picked up by the gamma walkover survey, unless an extremely tight grid spacing had been used with a very large number of samples. For locations where soil samples yielded concentrations greater than 5 pCi/g, it would still have been unclear whether the surrounding 100-square-meter area was, on average, above 5 pCi/g. No information would have been available about the lateral extent of individual areas to support their excavation. The use of gamma walkover surveys without a GPS would have allowed elevated areas to be identified, flagged, and sampled. The gamma walkover data, however, could not have been used to determine whether 100-square-meter areas were, on average, over the guidelines, nor would it have provided much information about the extent of contamination for flagged areas that ultimately yielded sample results above 5 pCi/g. As a historical note, the site was initially remediated using gross gamma screens without a GPS.

### *Completeness of Site Documentation*

The use of ASAP techniques and dynamic work plans means that the progress of data collection and remediation work is not explicitly planned out before work begins. Consequently, it is extremely important that the actions taken and data collected are carefully documented. Gamma walkovers combined with a GPS that logs data provide the opportunity for generating this type of documentation. The GPS associated with the gamma walkover can perform multiple uses, including locating the positions of direct measurements or soil sampling and identifying the boundary of

excavations. The Michigan demonstration and figures contained in this report illustrate this capability (e.g., Figures 2.13 and 2.16).

### *Tightened Schedules*

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) approaches to hazardous waste site characterization and remediation are based on a staged, sequential approach to decision making, with distinct time gaps between stages. In the case of NORM contamination, contaminants are already known and cleanup requirements typically preestablished. In this context, opportunity exists to blend characterization and restoration into one overall data collection, excavation, and remediation program. The advantages are greatly reduced overall project schedules and reductions in documentation and mobilization costs. Reliance on off-site *ex situ* laboratory analyses of soil samples makes this kind of integration difficult because of sample turnaround times. In the case of the Michigan demonstration, using real-time data collection and ASAP techniques, the bulk of the characterization, excavation, and final status closure work was completed in one round of fieldwork. Data collection moved directly from site characterization, to support of excavation work, to final status survey work. The only exceptions to this were a preliminary site visit to establish background conditions at the site. A subsequent visit to the site was conducted after the main work had been performed to rectify a few data gaps that were identified after the field crews had been demobilized.

**Table 2.1 Relationship between Gross Activity (miniFIDLER) and Measured Ra-226 Concentrations**

Ra-226 Value (pCi/g)	miniFIDLER Gross Activity Range (cpm)	Total No. of Samples	No. of Samples above Ra-226 Value	Fraction of Samples above Ra-226 Value	Lower Trigger (cpm)	Upper Trigger (cpm)
5	<1,800	8	0	0	1,800	2,500
	1,800-2,500	9	7	0.78		
	>2,500	32	32	1.00		
15	<4,000	22	0	0	4,000	7,000
	4,000-7,000	4	3	0.75		
	>7,000	23	22	0.96		
30	<7,000	26	0	0	7,000	16,000
	7,000-16,000	8	6	0.75		
	>16,000	15	15	1.00		
50	<11,000	27	0	0	11,000	19,000
	11,000-19,000	7	3	0.43		
	>19,000	15	15	1.00		
100	<19,000	34	0	0	19,000	25,000
	19,000-25,000	5	1	0.20		
	>25,000	10	10	1.00		

**Table 2.2 Pre- and Postexcavation *In Situ* HPGe Data for Elevated Areas**

Location	Preexcavation Ra-226 (pCi/g)	Postexcavation Ra-226 (pCi/g)
Northwest Corner	4.9, 6.3	3.3
Northeast Corner	NA	1.0
Center West	NA	0.6, 2.6
Center East	NA	3.3
South of Fence	6.0	3.3

**Table 2.3 Summary Final Status Survey Results**

Unit	RadInSoil Ra-226 (pCi/g)			ACL Ra-226 (pCi/g)			<i>In Situ</i> HPGe Ra-226 (pCi/g)		
	Min	Max	Aver	Min	Max	Aver	Min	Max	Aver
1	0.0	9.6	1.6	0.4	3.9	1.3	0.2	2.0	1.0
2	0.3	1.4	0.7						
3	0.3	2.7	0.9						
4	0.4	1.1	0.7						
5	0.4	2.0	0.8						
6	0.3	5.2	1.3	0.5	18.4	2.9	0.5	4.8	1.7
7	0.4	1.4	0.7						
8	0.3	1.1	0.7						

**Table 2.4 Summary Drum Information**

Drum	Date	Drum Label	Screening Results	Pan	Comments
1	14-Oct	80 MR	80 microrem/h	1	Wet
2	14-Oct	110 MR	60 microrem/h	1	Cracked
3	14-Oct	80 MR	60 microrem/h	1	Cracked
4	14-Oct	114	10 microrem/h	1	Wet
5	14-Oct	56 MR	12 microrem/h	2	Cracked
6	14-Oct	80 MR	25 microrem/h	2	
7	14-Oct	90	25 microrem/h	2	Cracked
8	14-Oct	75 MR	80 microrem/h	2	Wet
9	14-Oct	No label	150 microrem/h	2	
10	14-Oct	80 MR	45 microrem/h	2	Cracked
11	14-Oct	RM009	50 microrem/h	3	
12	14-Oct	RM009	25 microrem/h	3	Wet
13	14-Oct	12 MR	25 microrem/h	3	Wet
14	14-Oct	RM145	50 microrem/h	3	
15	14-Oct	RM015	60 microrem/h	3	
16	14-Oct	RM013	60 microrem/h	3	
17	14-Oct	55 MR	65 microrem/h	4	
18	14-Oct	RM110	80 microrem/h	4	
19	14-Oct	MR048	55 microrem/h	4	
20	14-Oct	70 RM	30 microrem/h	4	
21	14-Oct	RM028	55 microrem/h	4	
22	14-Oct	No label	200 microrem/h	5	
23	14-Oct	150 MR	300 microrem/h	5	
24	14-Oct	No label	300 microrem/h	5	
25	14-Oct	No label	200 microrem/h	5	
26	14-Oct	No label	40 microrem/h	6	
27	14-Oct	80 MR	40 microrem/h	6	
28	14-Oct	RM 110	40 microrem/h	6	
29	14-Oct	20 MR	40 microrem/h	6	
30	14-Oct	60 MR	40 microrem/h	6	
31	15-Oct	No label	40 microrem/h	7	Cracked
32	15-Oct	25 MR	40 microrem/h	7	Cracked
33	15-Oct	RM 011	20 microrem/h	7	
34	15-Oct	No label	80 microrem/h	7	Low volume
36	15-Oct	80	20 microrem/h	7	
42	15-Oct	RM038	80 microrem/h	7	
43	15-Oct	48 MR	50 microrem/h	7	Half Full
37	15-Oct	200	200 microrem/h	8	Cracked
38	15-Oct	68	200 microrem/h	8	Wet
39	15-Oct	MR 115	200 microrem/h	8	
40	15-Oct	70 MR	100 microrem/h	8	
41	15-Oct	MR 109	200 microrem/h	8	
44	15-Oct	100 MR	100 microrem/h	9	
45	15-Oct	90 MR	100 microrem/h	9	
46	15-Oct	50 MR	100 microrem/h	9	
48	15-Oct	60 MR	150 microrem/h	9	
49	15-Oct	310	250 KCPM	10	Cracked



**Table 2.4 (cont.) Summary Drum Information**

Drum	Date	Drum Label	Screening Results	Pan	Comments
50	15-Oct	360 MR	250 KCPM	10	Cracked
51	15-Oct	260 MR	800 microrem/h	10	Fishy smell
52	15-Oct	300 MR	800 microrem/h	10	Some black material, fishy smell
53	15-Oct	No label	800 microrem/h	10	Wet, some black material, fishy smell
54	15-Oct	110 MR	20 microrem/h	11	
55	15-Oct	70 MR	10 KCPM	11	
56	15-Oct	MR 30	10 KCPM	11	
57	15-Oct	No label	10 KCPM	11	
58	15-Oct	No label	--	11	
59	15-Oct	No label	100 microrem/h, 20 KCPM	11	
60	15-Oct	No label	30 KCPM	12	Cracked
61	15-Oct	No label	2 KCPM	12	Cracked
62	15-Oct	70	20 KCPM	12	Cracked
63	15-Oct	100	25 KCPM	12	Cracked
64	15-Oct	MR 80	17 KCPM	12	
65	15-Oct	No label	20 KCPM	12	
66	15-Oct	No label	20 KCPM	13	Cracked
NA	15-Oct	Not available	not available	13	Surface soil from drum area
67	15-Oct	80 MR	20 KCPM	13	Cracked
68	15-Oct	59	15 KCPM	13	Wet
69	16-Oct	280 MR	150 KCPM	14	Cracked
70	16-Oct	600	200 KCPM	14	Cracked
71	16-Oct	No label	100 KCPM	14	Cracked
72	16-Oct	500 MR	150 KCPM	14	Cracked
73	16-Oct	110 MR	50 KCPM	14	Cracked
74	16-Oct	250 MR	100 KCPM	15	Cracked
75	16-Oct	No label	75 KCPM	15	
76	16-Oct	100 MR	100 KCPM	15	
77	16-Oct	115 MR	100 KCPM, 150 microrem/h	15	
78	16-Oct	No label	100 KCPM	15	Wet
79	19-Oct	No label	40 KCPM	16	
80	19-Oct	60 MR	20 KCPM	16	
81	19-Oct	60 MR	30 KCPM	16	
82	19-Oct	No label	30 KCPM	16	Cracked
83	19-Oct	100 MR	30 KCPM	16	
84	19-Oct	320 MR	50 KCPM	16	
85	19-Oct	50 MR	20 KCPM	17	
86	19-Oct	No label	50 KCPM	17	
87	19-Oct	100 MR	20 KCPM	17	
88	19-Oct	No label	20 KCPM	17	
89	19-Oct	50 MR	30 KCPM	17	
90	19-Oct	100 MR	20 KCPM	17	
91	19-Oct	No label	100 KCPM	18	Cracked
92	19-Oct	400 MR	100 KCPM	18	Cracked
93	19-Oct	400 MR	100 KCPM	18	Cracked
94	19-Oct	No label	100 KCPM	18	Cracked
95	19-Oct	No label	100 KCPM	18	Cracked

**Table 2.4 (cont.) Summary Drum Information**

Drum	Date	Drum Label	Screening Results	Pan	Comments
96	19-Oct	No label	100 KCPM	18	Cracked
97	19-Oct	No label	100 KCPM	19	Cracked
98	19-Oct	No label	100 KCPM	19	Cracked
99	19-Oct	140 MR	100 KCPM	19	Cracked
100	19-Oct	No label	100 KCPM	19	Cracked
101	19-Oct	No label	100 KCPM	19	Cracked
102	19-Oct	No label	5 KCPM	20	Cracked
103	19-Oct	40 MR	20 KCPM	20	Cracked
104	19-Oct	No label	15 KCPM	20	Cracked
105	19-Oct	130 MR	30 KCPM	20	
106	19-Oct	100 MR	20 KCPM	20	
107	19-Oct	60 MR	10 KCPM	21	
108	19-Oct	135 MR	10 KCPM	21	Low volume
109	19-Oct	No label	10 KCPM	21	1 ft solids, 2 ft water
110	19-Oct	30 MR	15 KCPM	21	
111	19-Oct	50 MR	20 KCPM	21	
112	19-Oct	30 MR	10 KCPM	21	
113	19-Oct	80 MR	10 KCPM	21	
114	19-Oct	30 MR	5 KCPM	22	
115	19-Oct	75 MR	10 KCPM	22	Wet
116	19-Oct	100 MR	40 KCPM	22	
117	19-Oct	No label	5 KCPM	22	
118	19-Oct	50 MR	10 KCPM	22	
119	19-Oct	80 MR	5 KCPM	22	
120	19-Oct	70 MR	20 KCPM, 30 microrem/h	23	
121	19-Oct	80 MR	20 KCPM, 20 microrem/h	23	
122	19-Oct	60 MR	5 KCPM	23	Half full
123	19-Oct	400 MR	200 KCPM	23	
124	19-Oct	60 MR	100 KCPM	23	Wet
125	19-Oct	400 MR	100 KCPM	23	
126	20-Oct	400 MR	100 KCPM	24	
127	20-Oct	150 MR	100 KCPM	24	
128	20-Oct	260 MR	100 KCPM	24	
129	20-Oct	1000 MR	100 KCPM	24	
130	20-Oct	150 MR	200 KCPM	24	
131	20-Oct	100 MR	100 KCPM	25	
132	20-Oct	200 MR	50 KCPM	25	
133	20-Oct	60 MR	100 KCPM	25	
134	20-Oct	170 MR	100 KCPM, 210 microrem/h	25	
135	20-Oct	230 MR	40 KCPM	25	
136	20-Oct	No label	150 KCPM	25	2 inches residue, 4 inches water
137	20-Oct	100 MR	35 KCPM	26	
138	20-Oct	800 MR	80 KCPM	26	Some grey sludge
139	20-Oct	1100 MR	200 KCPM	26	
140	20-Oct	320 MR	100 KCPM	26	
141	20-Oct	320 MR	150 KCPM	26	
142	20-Oct	2100 MR	10,000 microrem/h	27	

**Table 2.4 (cont.) Summary Drum Information**

Drum	Date	Drum Label	Screening Results	Pan	Comments
143	20-Oct	900 MR	10,000 microrem/h	27	
144	20-Oct	430 MR	300 KCPM	27	Some grey sludge
145	20-Oct	800 MR	4,000 microrem/h	27	
146	20-Oct	No label	2,000 microrem/h	27	Wet, full of fibery excelsior & sludge
147	20-Oct	No label	500 KCPM	28	Wet, full of fibery excelsior & sludge
148	20-Oct	No label	300 KCPM	28	Wet, full of fibery excelsior & sludge
35	20-Oct	No label	50 microrem/h	28	Contents oily
47	20-Oct	180 MR	150 microrem/h	28	Contents oily

Note: KCPM stands for thousands of counts per minute.

**Table 2.5 Summary Information for Soil Pans**

Pan	Date	Depth (in.)	Volume (yd <sup>3</sup> )	<i>In Situ</i> HPGe Ra-226 (pCi/g)	<i>Ex Situ</i> HPGe Marinelli		ACL		DEQ		NORM ISI		Pan Sample Type
					Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	
1	14-Oct	4	0.94	30	NA	NA	42	24	35	18	35	14	5-point pattern (5 samples)
2	14-Oct	6	1.42	68	NA	NA	135	131	67	14	64	19	5-point pattern (5 samples)
3	14-Oct	6	1.42	25	60	77	NA	NA	NA	NA	NA	NA	5-point pattern (5 samples)
4	14-Oct	6	1.42	38	NA	NA	NA	NA	NA	NA	NA	NA	None
5	14-Oct	6	1.42	157	NA	NA	NA	NA	138	NA	NA	NA	5-point composite (single sample)
6	14-Oct	6	1.42	31	NA	NA	NA	NA	NA	NA	NA	NA	None
7	15-Oct	6	1.42	14	17	NA	NA	NA	14	NA	NA	NA	5-point composite (single sample)
8	15-Oct	6	1.42	71	28	NA	NA	NA	81	NA	NA	NA	5-point composite (single sample)
9	15-Oct	6	1.42	84	68	NA	NA	NA	42	NA	NA	NA	5-point composite (single sample)
10	15-Oct	5	1.18	317	436	311	NA	NA	289	128	292	134	5-point pattern (5 samples)
11	15-Oct	6	1.42	54	927	NA	NA	NA	37	NA	NA	NA	5-point composite (single sample)
12	15-Oct	7	1.65	75	46	NA	NA	NA	85	NA	NA	NA	5-point composite (single sample)
13	15-Oct	6	1.42	35	20	NA	NA	NA	22	NA	NA	NA	5-point composite (single sample)
14	16-Oct	6	1.42	187	169	196	NA	NA	179	71	281	310	5-point pattern (5 samples)
15	16-Oct	6	1.42	75	77	NA	NA	NA	101	NA	NA	NA	5-point composite (single sample)
16	19-Oct	6	1.42	96	64	NA	NA	NA	127	NA	NA	NA	5-point composite (single sample)
17	19-Oct	6	1.42	65	53	NA	NA	NA	89	NA	NA	NA	5-point composite (single sample)
18	19-Oct	6	1.42	252	170	NA	NA	NA	500	NA	NA	NA	5-point composite (single sample)
19	19-Oct	6	1.42	129	183	NA	NA	NA	209	NA	NA	NA	5-point composite (single sample)
20	19-Oct	6	1.42	36	22	NA	NA	NA	39	NA	NA	NA	5-point composite (single sample)
21	19-Oct	6	1.42	40	34	NA	NA	NA	50	NA	NA	NA	5-point composite (single sample)
22	19-Oct	6	1.42	30	17	NA	NA	NA	24	NA	NA	NA	5-point composite (single sample)
23	19-Oct	6	1.42	121	45	NA	NA	NA	48	NA	NA	NA	5-point composite (single sample)
24	20-Oct	6	1.42	194	140	NA	NA	NA	219	NA	NA	NA	5-point composite (single sample)
25	20-Oct	5.5	1.30	183	155	NA	NA	NA	144	NA	NA	NA	5-point composite (single sample)
26	20-Oct	6	1.42	186	182	NA	NA	NA	207	NA	NA	NA	5-point composite (single sample)
27	20-Oct	5	1.18	775	443	348	NA	NA	824	601	504	341	9-point pattern (9 samples)
28	20-Oct	4	0.94	1,500	NA	NA	NA	NA	2,000	NA	1,293	NA	5-point composite (single sample)
29	22-Oct	5.5	1.30	18	NA	NA	NA	NA	22	NA	NA	NA	5-point composite (single sample)

**Table 2.5 (cont.) Summary Information for Soil Pans**

Pan	Date	Depth (in.)	Volume (yd <sup>3</sup> )	<i>In Situ</i> HPGe Ra-226 (pCi/g)	<i>Ex Situ</i> HPGe Marinelli		ACL		DEQ		NORM ISI		Pan Sample Type
					Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	Average Ra-226 (pCi/g)	St.Dev. (pCi/g)	
30	22-Oct	6	1.42	16	NA	NA	NA	NA	15	NA	NA	NA	5-point composite (single sample)
31	22-Oct	6	1.42	11	NA	NA	NA	NA	14	NA	NA	NA	5-point composite (single sample)
32	22-Oct	6	1.42	15	NA	NA	NA	NA	12	NA	NA	NA	5-point composite (single sample)
33	23-Oct	7.5	1.77	22	NA	NA	16	NA	13	NA	NA	NA	5-point composite (single sample)
34	23-Oct	6.5	1.53	27	NA	NA	NA	NA	NA	NA	NA	NA	NA

**Table 2.6 Summary Information for Bulk Storage Bins**

Bin ID	Volume (yd <sup>3</sup> )	Average Ra-226 (pCi/g)	Comments
0 - 30	11.7	19	
30 - 50	9.4	35	
50 - 100	11.6	74	
100+	12.4	189	
Drums from Pan 27	1.2	775	Hot soils
Drums from Pan 28	0.9	1,500	Oil/NORM mixed
	Total: 47.2	Average: 129	

**Table 2.7 Comparison of RadInSoil Data with DEQ Results**

Location	RadInSoil Ra-226 (pCi/g)	DEQ Ra-226 (pCi/g)
BG01	0.60	0.27
BG02	1.00	0.41
BG03	0.70	0.60
BG06	0.90	0.65
BG07	0.70	0.59
H10A	1.50	0.24
H11	2.40	5.85
H12A	5.20	3.38
H13A	5.00	3.89
H16	5.60	2.42
H18	30.00	19.61
H1A	59.00	19.15
H21	33.00	162.41
H27	6.80	62.94
H28	6.00	273.35
H30	17.00	7.73
H37	2,240.00	928.64
H38	140.00	91.58
H3A	1.10	9.22
H49	8.70	8.43
H50	2.80	2.75
H6A	237.00	185.36
H7	4.90	116.33
H8A	2.30	24.62
H9A	19.20	6.72
Pan 10-1	192.00	520.66
Pan 10-2	508.00	269.79
Pan 10-3	290.00	197.22
Pan 10-4	251.00	278.75
Pan 10-5	206.00	191.84
Pan 1-1	8.00	25.25
Pan 1-2	53.00	49.35
Pan 1-3	49.00	51.55
Pan 1-4	35.00	28.04
Pan 14-1	186.00	821.26
Pan 14-2	196.00	147.09
Pan 14-3	284.00	257.05

**Table 2.7 (cont.) Comparison of RadInSoil Data with DEQ Results**

Location	RadInSoil Ra-226 (pCi/g)	DEQ Ra-226 (pCi/g)
Pan 14-4	111.00	87.80
Pan 14-5	116.00	89.92
Pan 1-5	31.00	22.30
Pan 2-1	49.00	95.23
Pan 2-2	71.00	60.47
Pan 2-3	63.00	57.11
Pan 2-4	88.00	45.35
Pan 2-5	65.00	60.30
Pan 27-1	1,480.00	747.09
Pan 27-2	432.00	329.81
Pan 27-3	493.00	526.33
Pan 27-4	1,470.00	637.83



**Table 2.8 Comparison of ACL and DEQ Split Sample Results**

Location	ACL Ra-226 (pCi/g)	DEQ Ra-226 (pCi/g)
BG01	0.49	0.60
BG02	0.39	1.00
BG03	0.62	0.70
BG06	0.61	0.90
BG07	0.33	0.70
H10A	0.77	1.50
H12A	2.78	5.20
H13A	6.50	5.00
H1A	93.30	59.00
H3A	6.31	1.10
H6A	51.30	237.00
H8A	1.63	2.30
H9A	9.74	19.20
Pan 1-1	8.60	8.00
Pan 1-2	62.60	53.00
Pan 1-3	50.30	49.00
Pan 1-4	62.10	35.00
Pan 1-5	27.60	31.00
Pan 2-1	362.00	49.00
Pan 2-2	133.00	71.00
Pan 2-3	63.10	63.00
Pan 2-4	57.60	88.00
Pan 2-5	57.80	65.00

**Table 2.9 RadInSoil Precision Data for Locations BG04 and H11**

Location	Count Time	Average Ra-226 (pCi/g)	Stand Dev. (pCi/g)	Stand. Dev. for Average (pCi/g)
BG 04	300	0.54	0.19	0.05
	600	0.49	0.12	0.03
H 11	120	6.74	0.35	0.10
	300	6.61	0.30	0.07



**Figure 2.1 Map of Michigan NORM Site**



**Figure 2.2 View of Site from South of Fence**





**Figure 2.3 Original Drummed Soils**



**Figure 2.4 Gamma Walkover Equipment**





**Figure 2.5** *In Situ* HPGe System



**Figure 2.6 NORM IS, Inc., RadInSoil Meter**





**Figure 2.7 Characterization Pans for Drummed Waste**

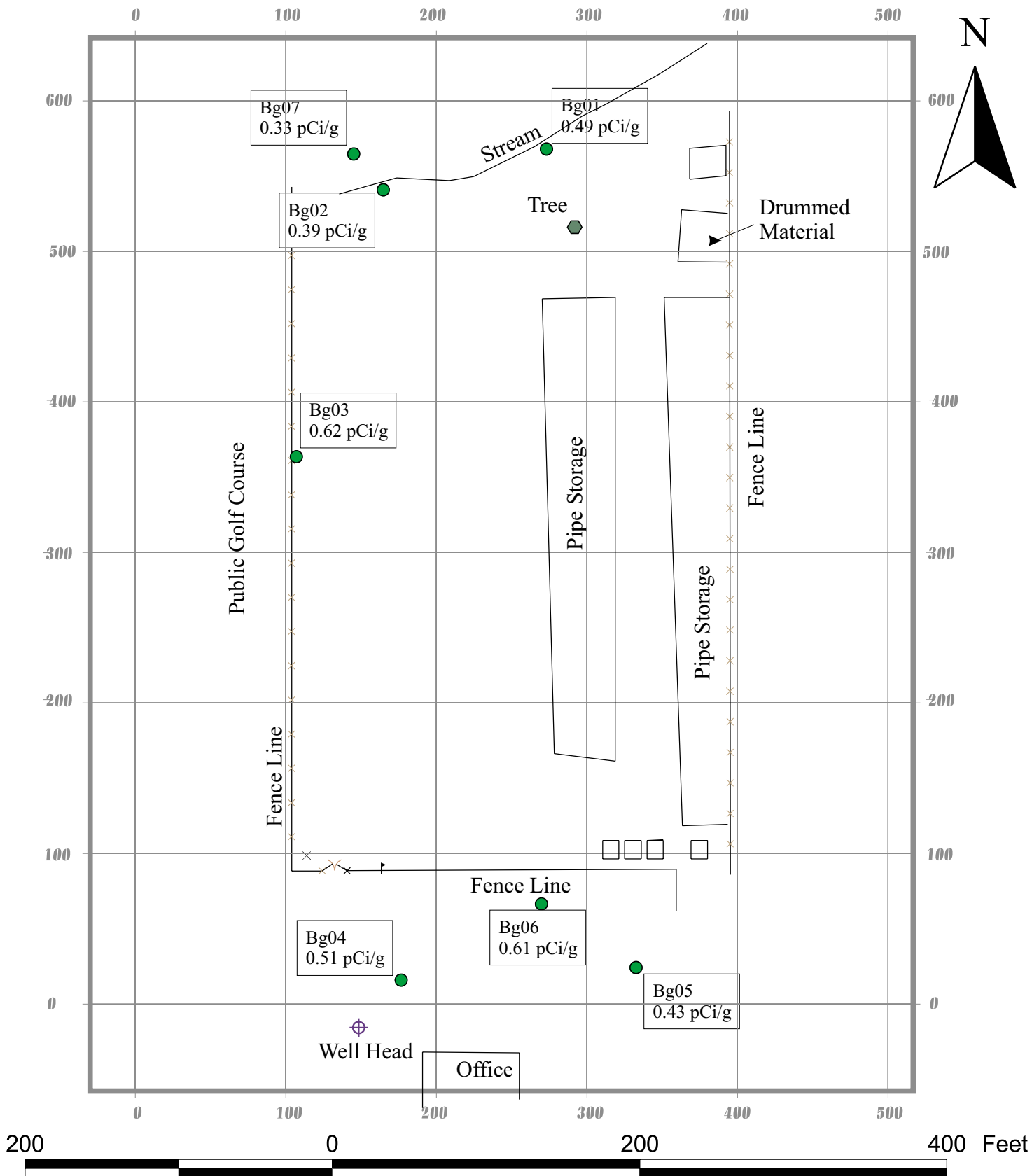


**Figure 2.8 RadInSoil Pan Characterization and Pan Composite Sample**

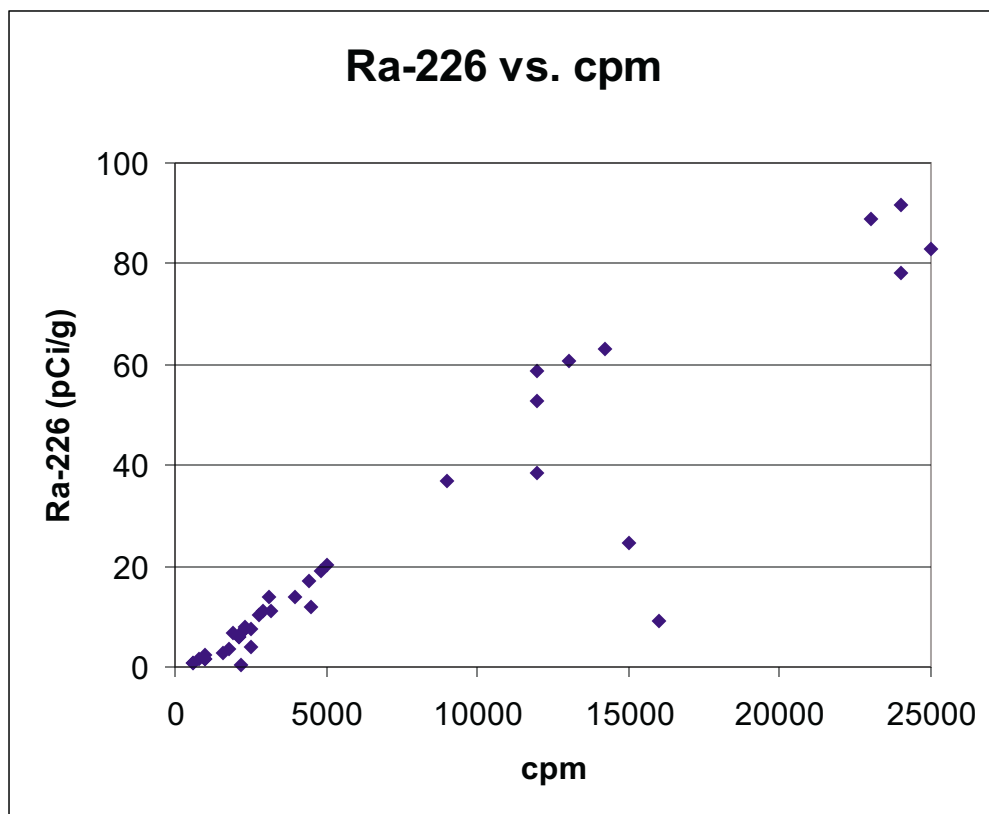




**Figure 2.9 Segregation of Pan Soils into Storage Bins**



**Figure 2.10 Background Soil Sample Locations and Results**



**Figure 2.11 Relationship between RadInSoil Ra-226 Concentrations and Observed Gross Activity**

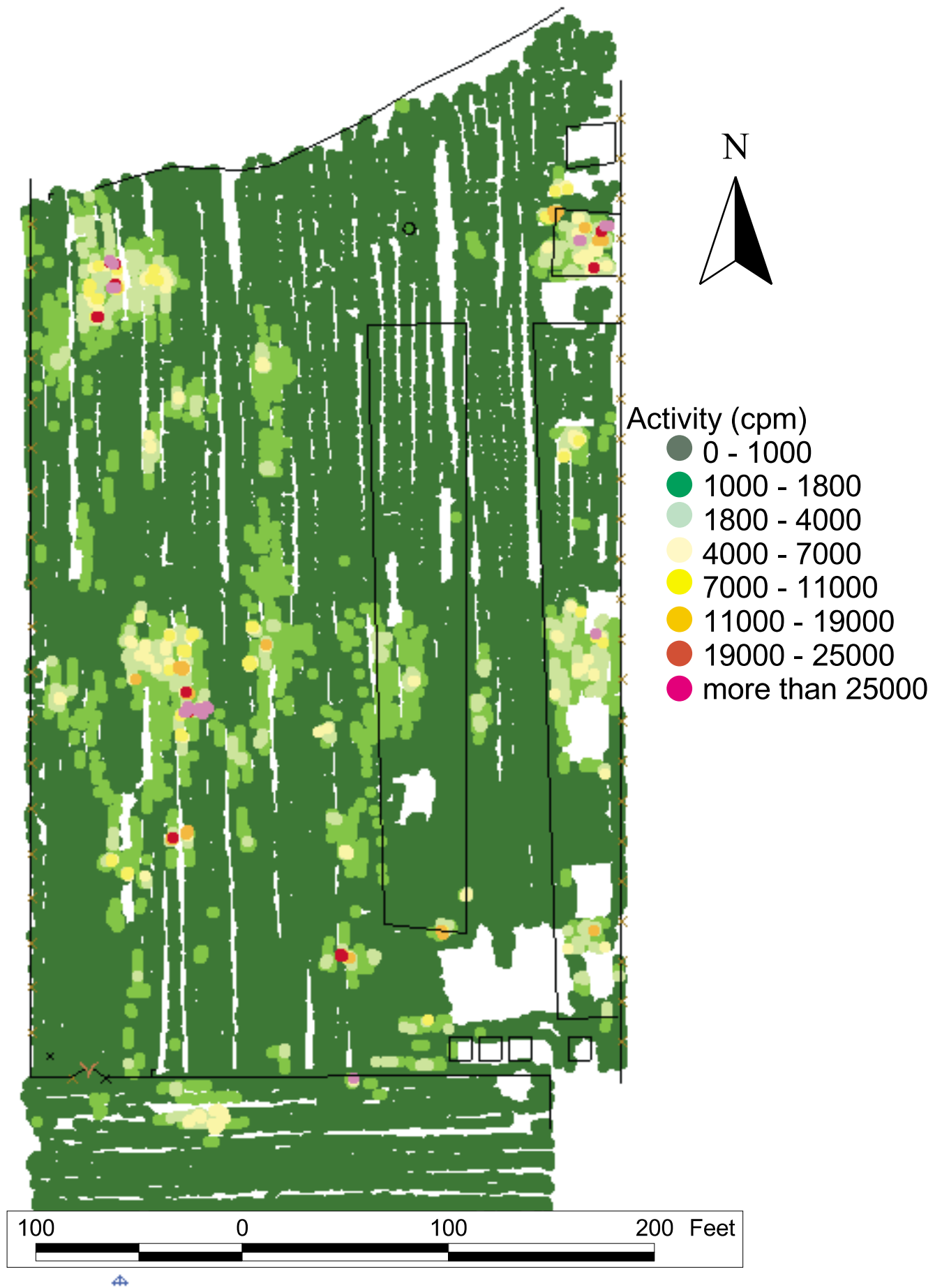


Figure 2.12 Preexcavation Gamma Walkover Results Color Coded Based on Trigger Levels

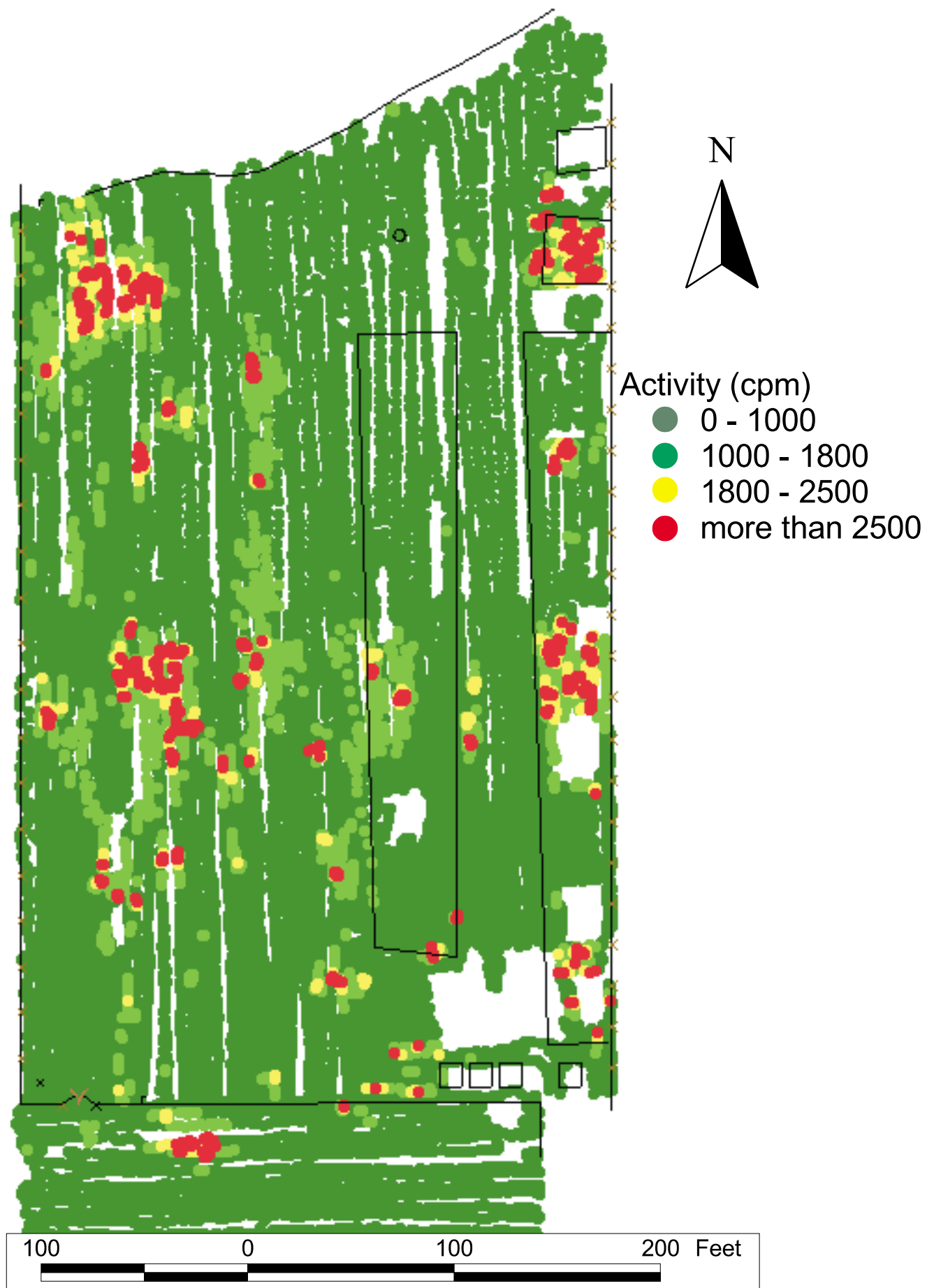
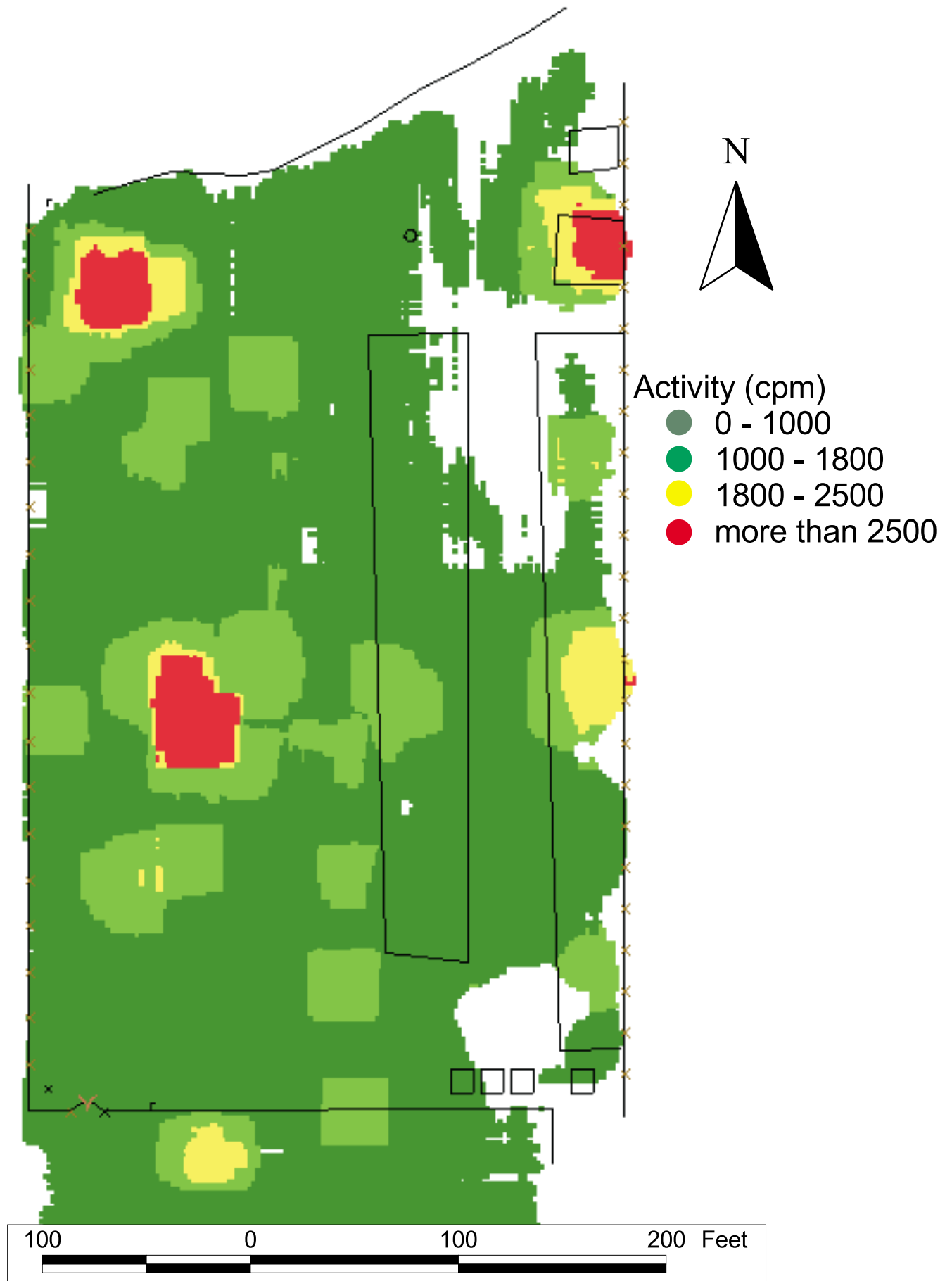
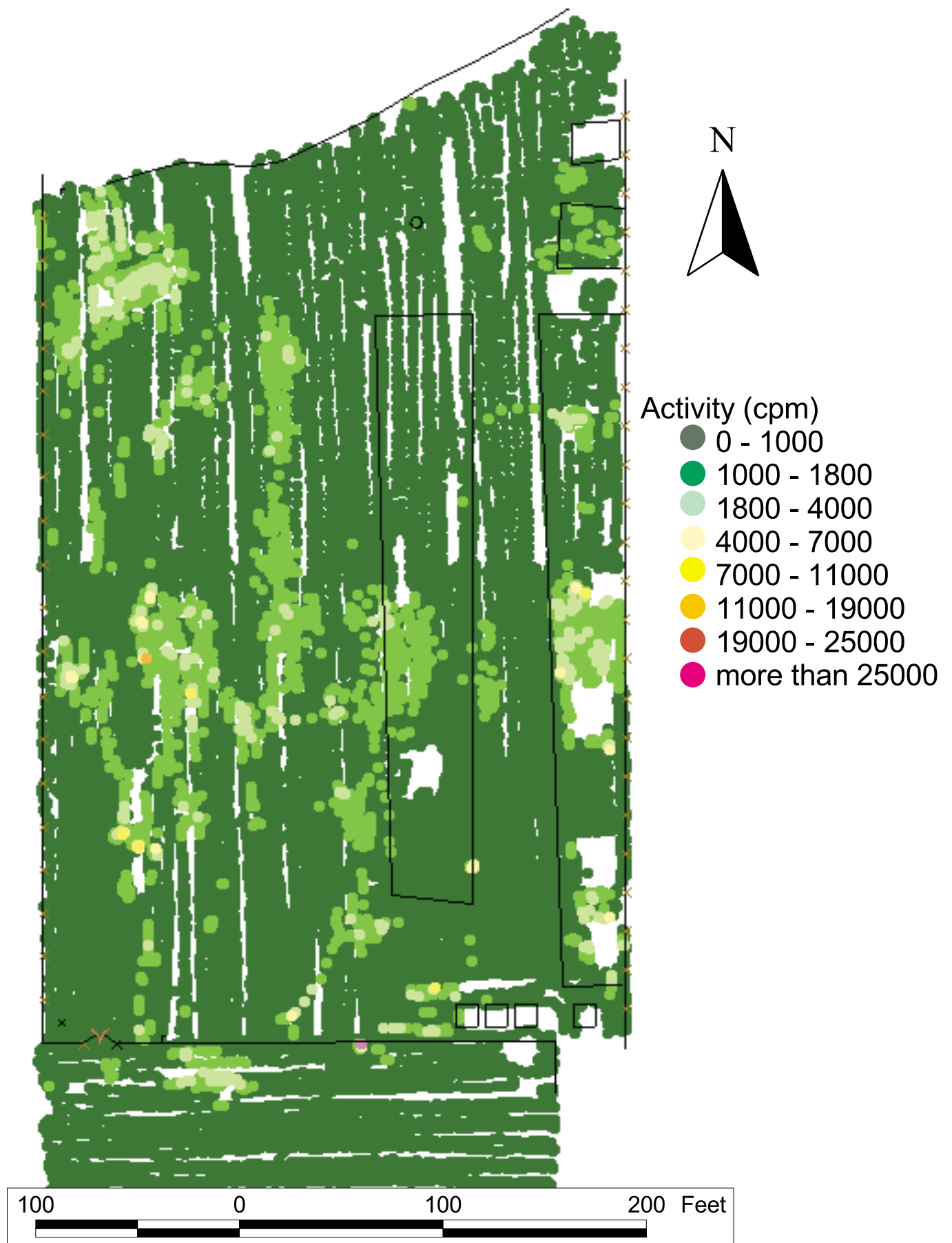


Figure 2.13 Preexcavation Gamma Walkover Results Color Coded Based on 5 pCi/g Cleanup Goal



**Figure 2.14 Preexcavation Gamma Walkover Results Spatially Averaged Over 100 Square Meters and Color Coded Based on 5 pCi/g Cleanup Goal**





**Figure 2.15 Postexcavation Gamma Walkover Results Color Coded Based on Trigger Levels**

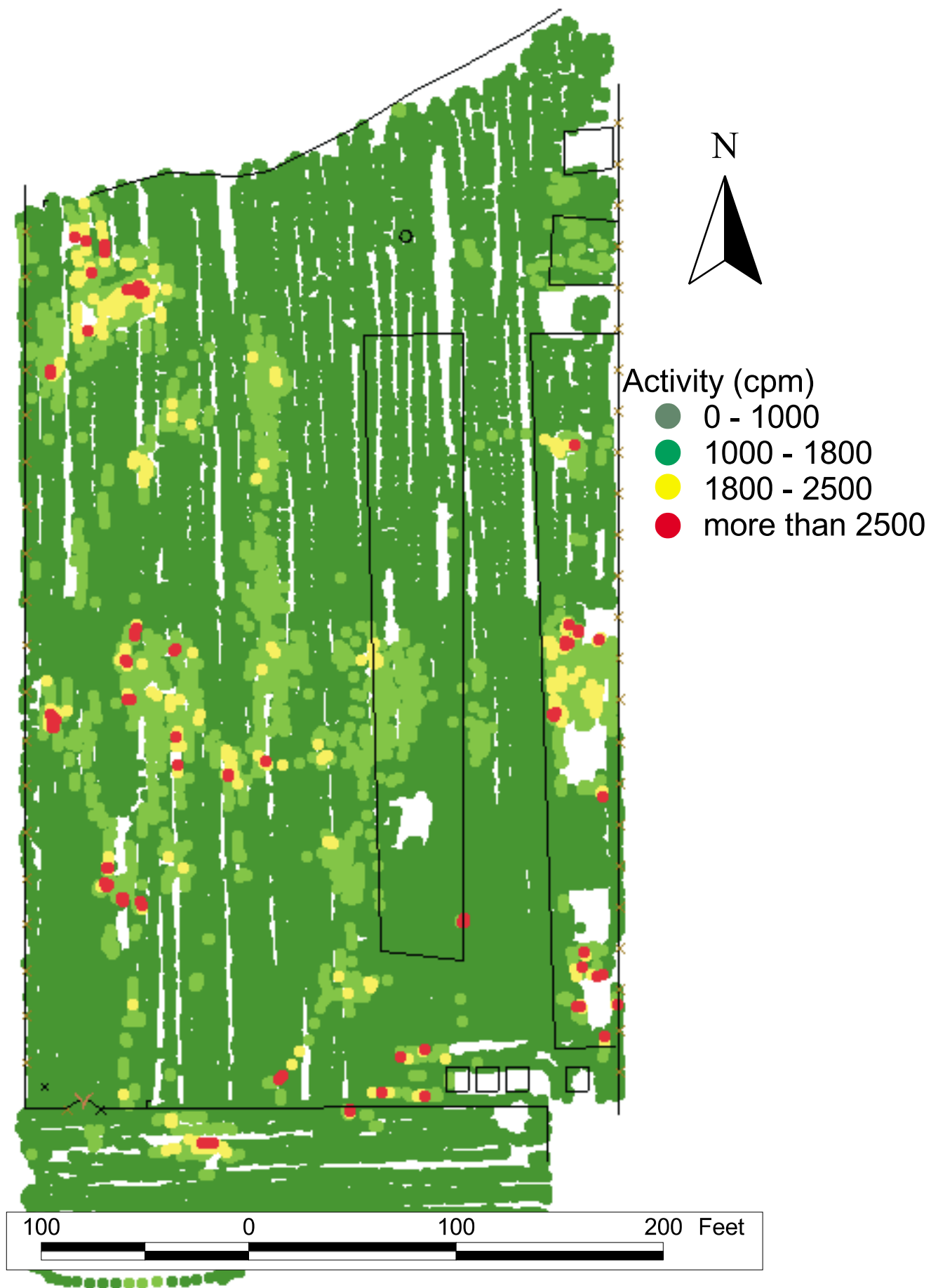
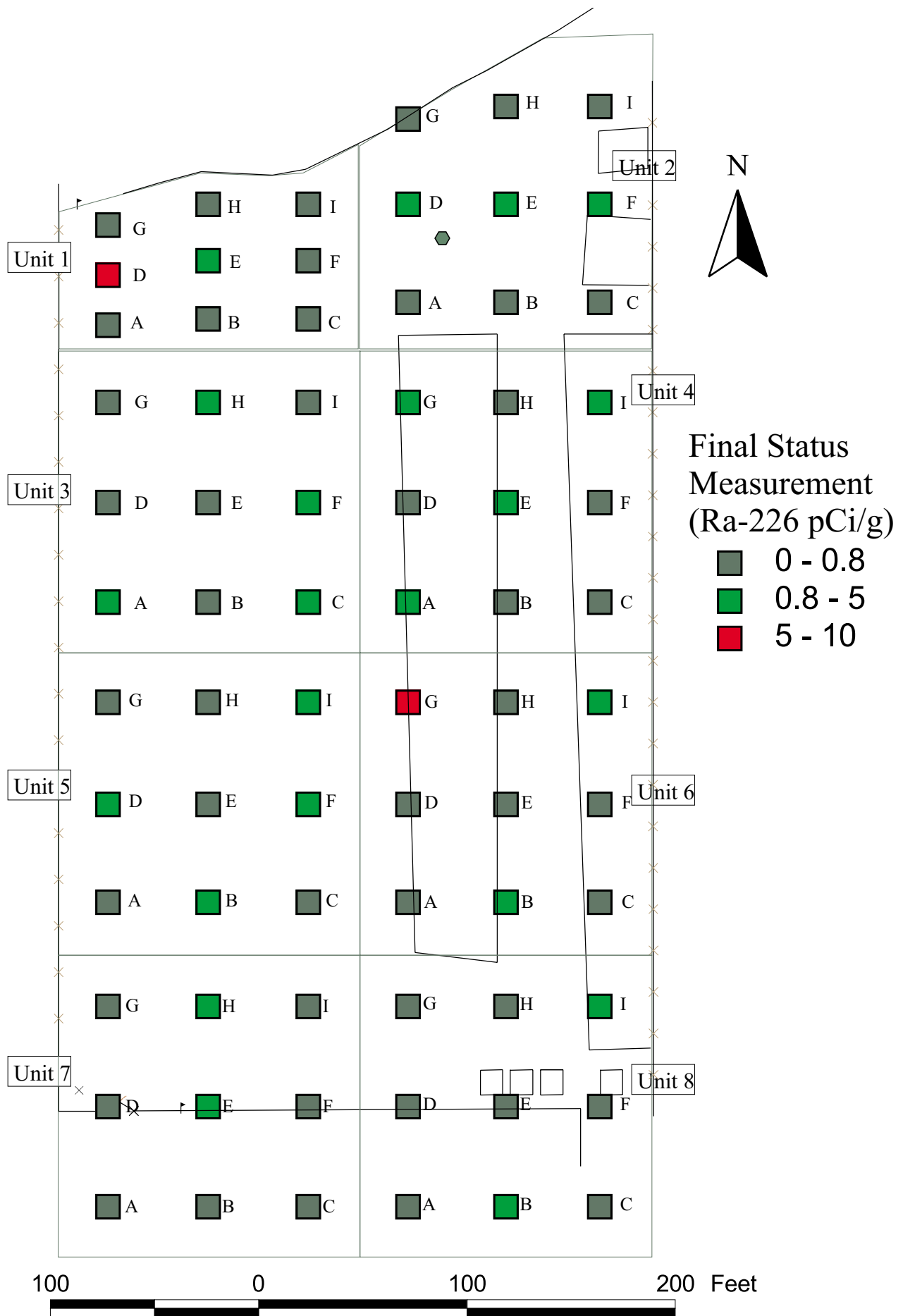


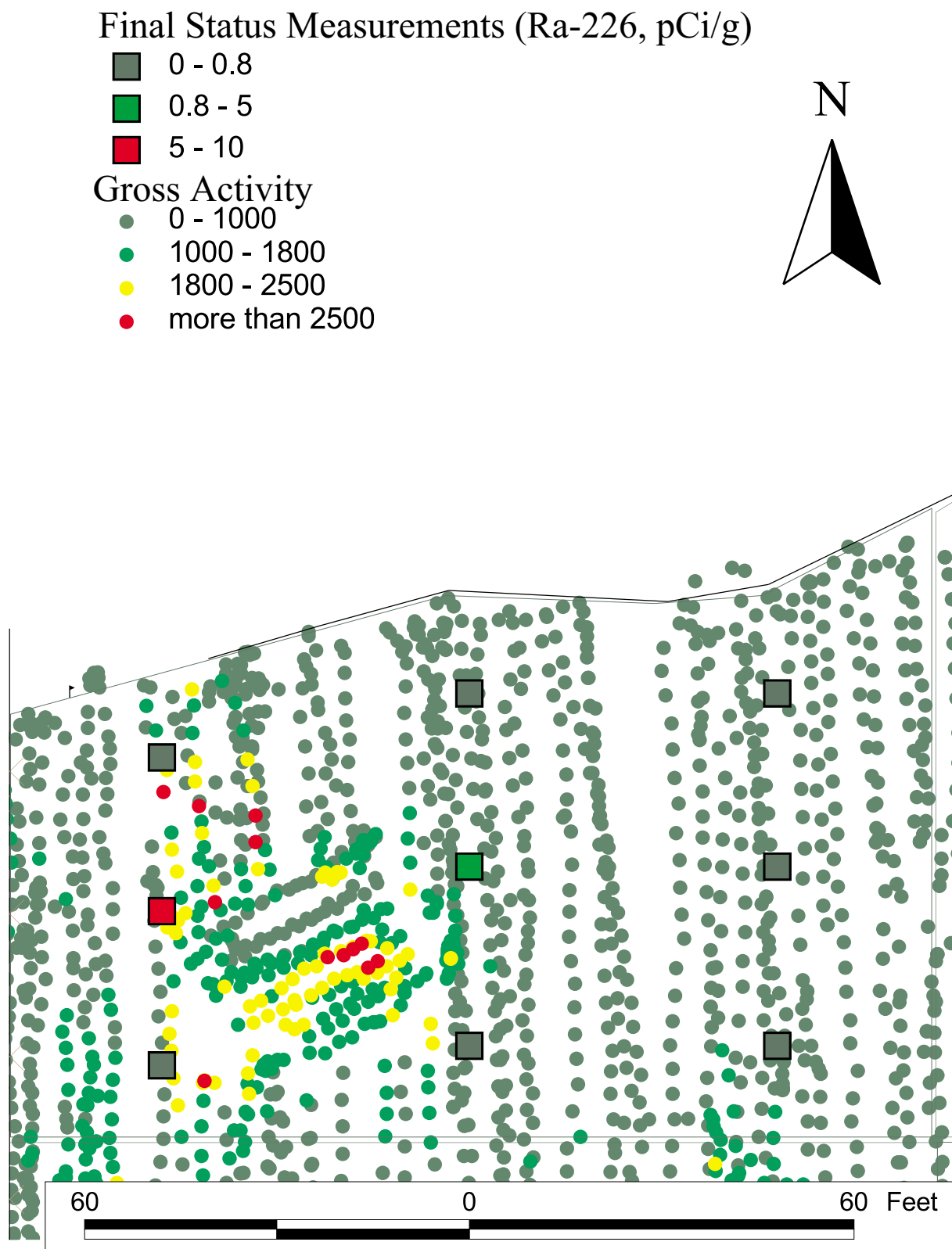
Figure 2.16 Postexcavation Gamma Walkover Results Color Coded Based on 5 pCi/g Cleanup Goal



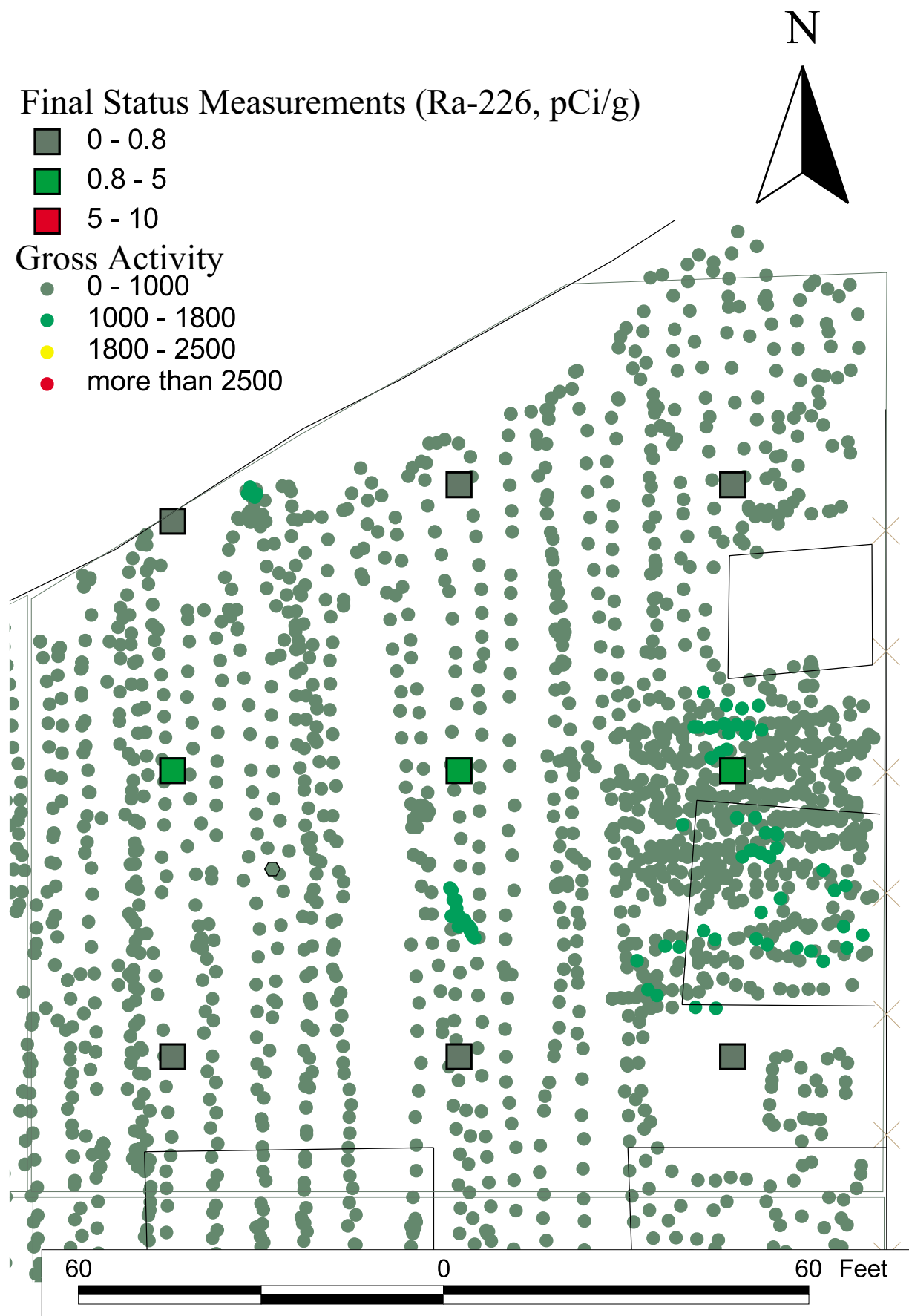
**Figure 2.17 Postexcavation Gamma Walkover Results Spatially Averaged over 100 Square Meters and Color Coded Based on 5 pCi/g Cleanup Goal**



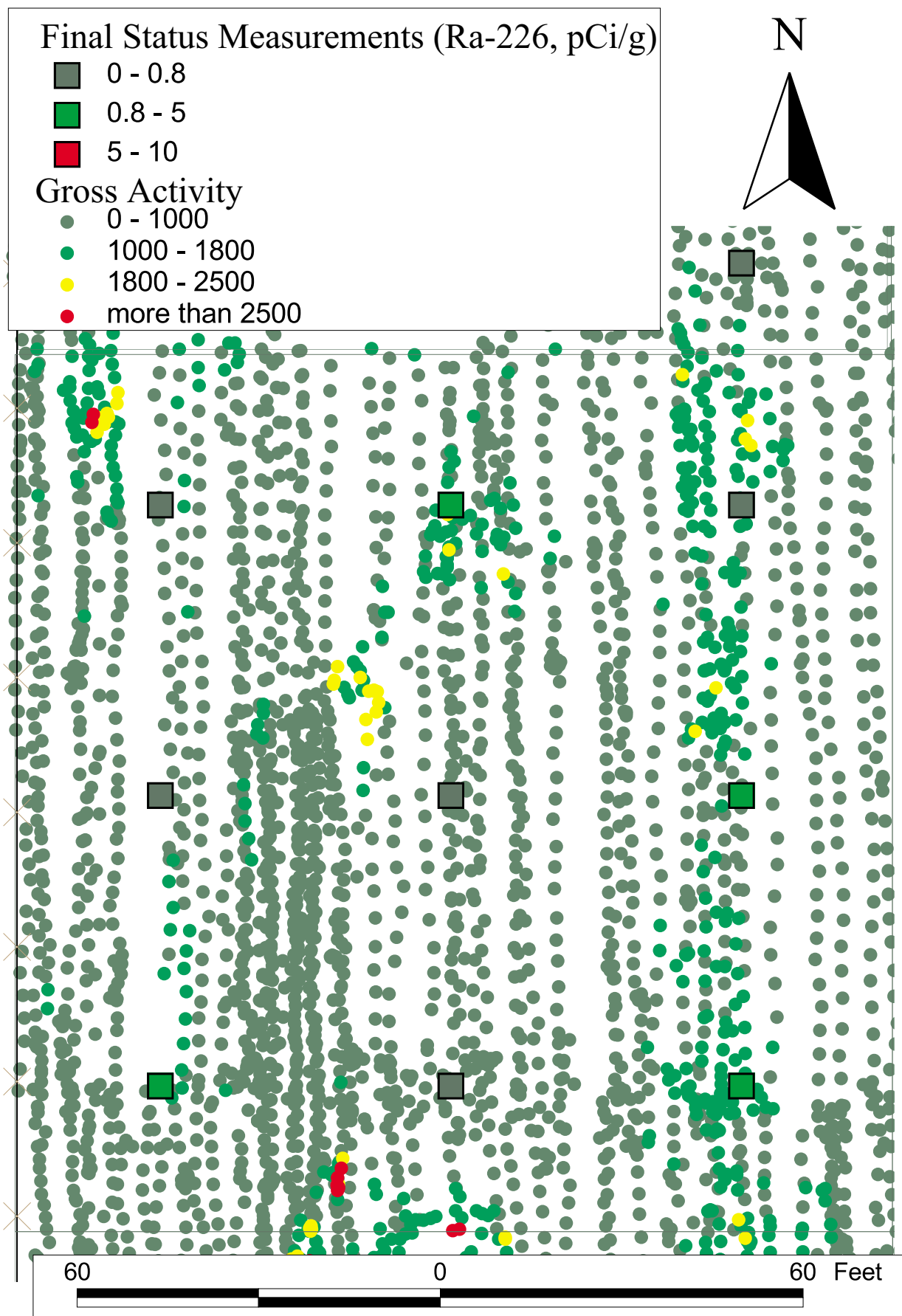
**Figure 2.18 Final Status Survey Units and Measurement Locations**



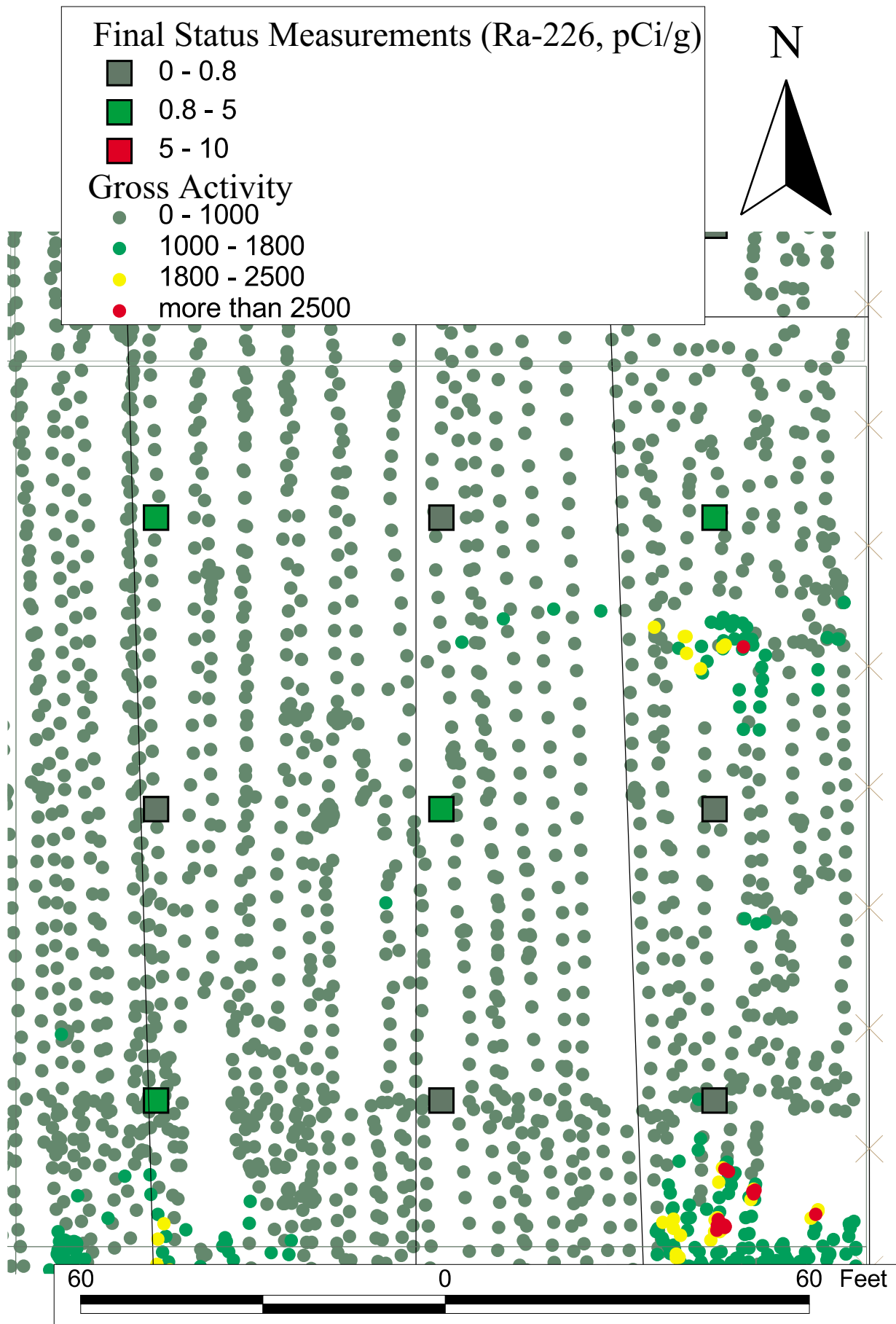
**Figure 2.19 Final Status Survey Unit 1 with Measurement Locations and Postexcavation Gamma Walkover Results**



**Figure 2.20 Final Status Survey Unit 2 with Measurement Locations and Postexcavation Gamma Walkover Results**

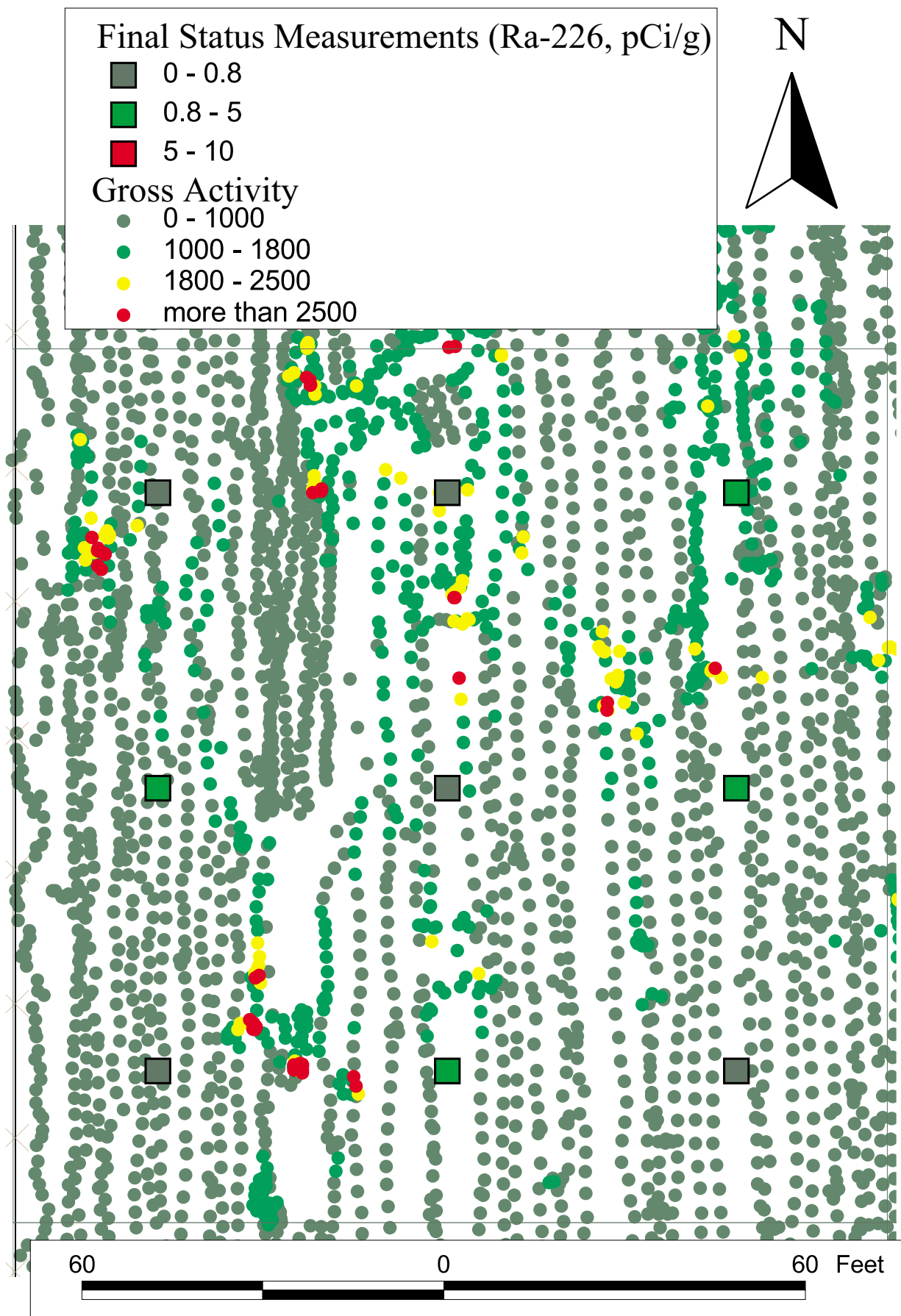


**Figure 2.21 Final Status Survey Unit 3 with Measurement Locations and Postexcavation Gamma Walkover Results**

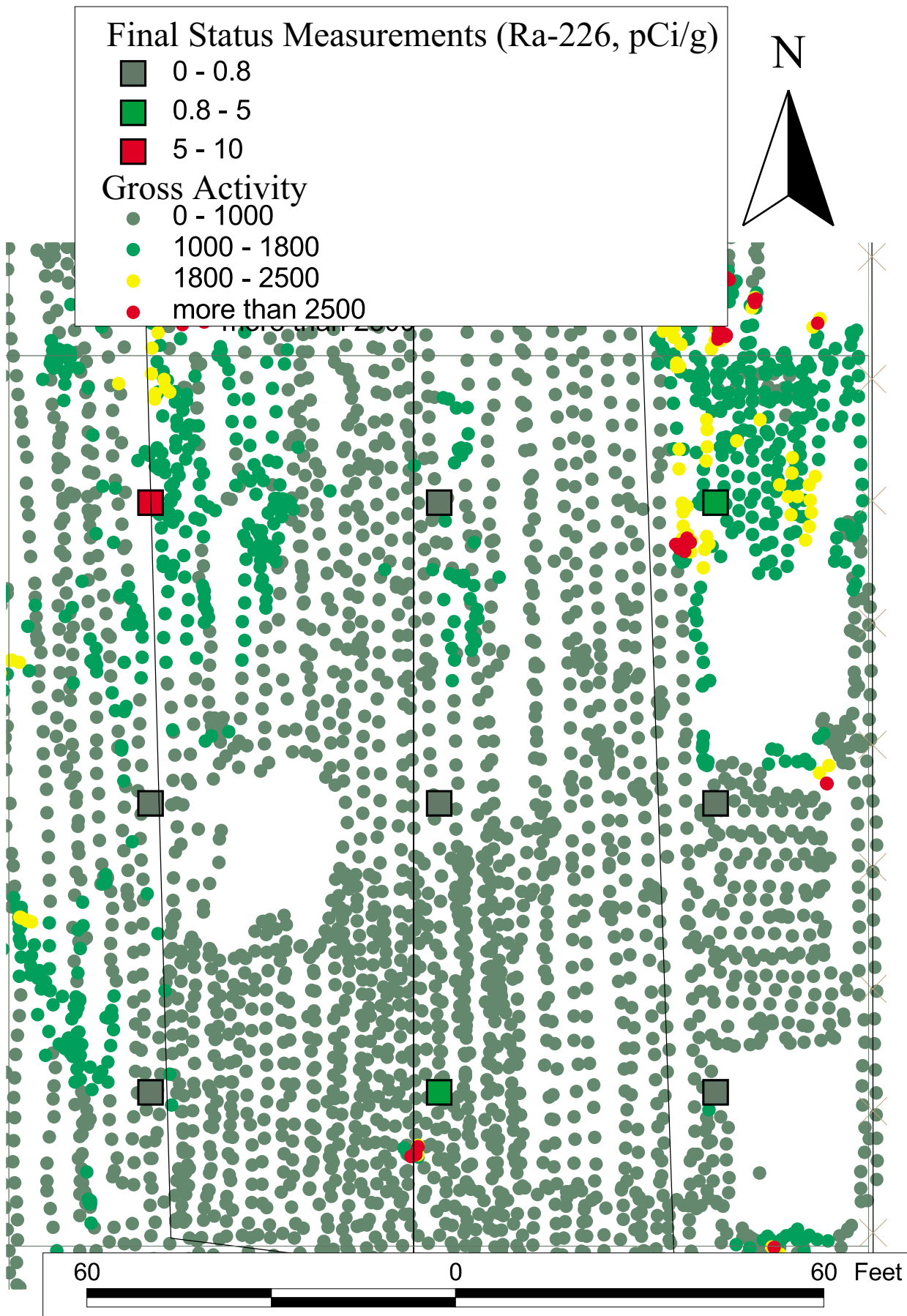


**Figure 2.22** Final Status Survey Unit 4 with Measurement Locations and Postexcavation Gamma Walkover Results

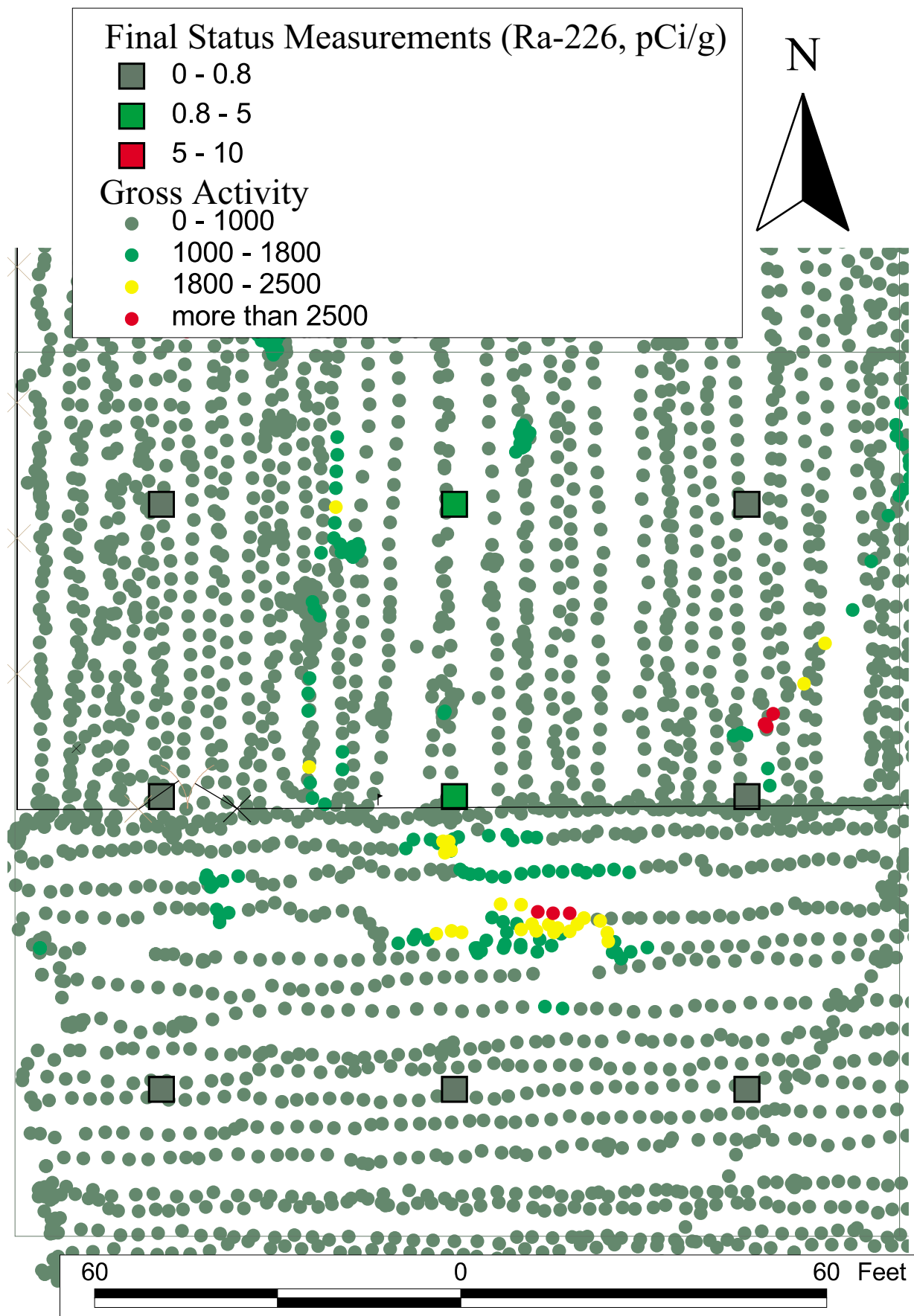




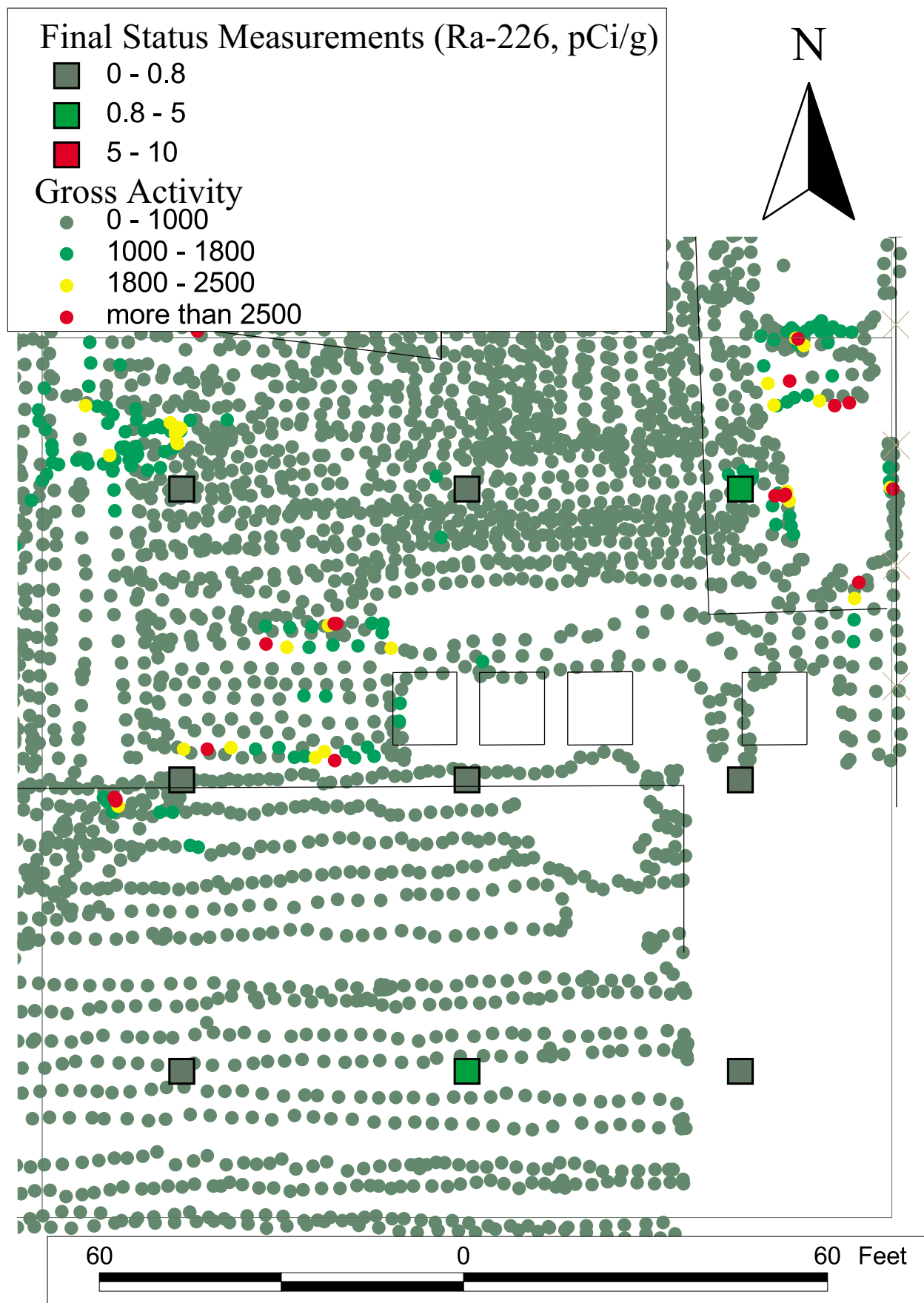
**Figure 2.23 Final Status Survey Unit 5 with Measurement Locations and Postexcavation Gamma Walkover Results**



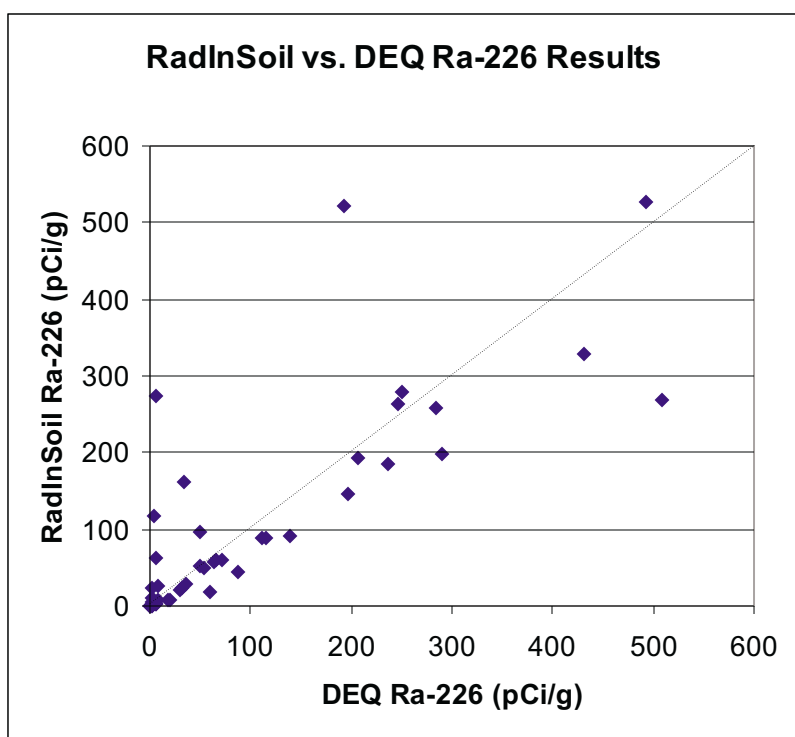
**Figure 2.24 Final Status Survey Unit 6 with Measurement Locations and Postexcavation Gamma Walkover Results**



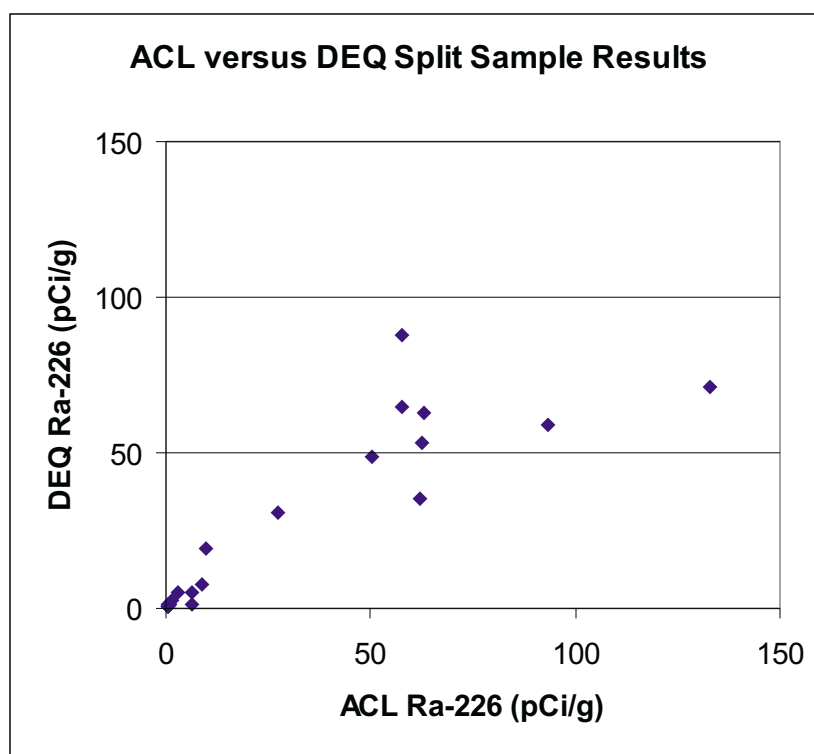
**Figure 2.25** Final Status Survey Unit 7 with Measurement Locations and Postexcavation Gamma Walkover Results



**Figure 2.26 Final Status Survey Unit 8 with Measurement Locations and Postexcavation Gamma Walkover Results**



**Figure 2.27 Comparison of RadInSoil Measurement Results with State of Michigan DEQ Results for Ra-226**



**Figure 2.28 Comparison of ACL and DEQ Ra-226 Results for Split Samples**

### 3 CONCLUSIONS AND SUMMARY

ASAP data collection programs rely on real-time data collection technologies and in-field decision support to guide the course of characterization and/or remediation work. ASAP techniques have particular application to NORM problems because of the relative abundance of real-time technologies appropriate for Ra-226. The demonstration work at a Michigan site made use of three real-time data collection technologies operating in an Adaptive Sampling and Analysis framework. These included a gamma walkover/GPS for complete surficial site coverage; *in situ* HPGe gamma spectroscopy for quantitative isotope-specific direct measurements; and an NaI-based direct measurement device called RadInSoil, specifically intended for NORM work.

The results from the Michigan demonstration establish that this type of approach can be very effective for NORM problems. The advantages include (1) greatly reduced per sample analytical costs; (2) a reduced reliance on soil sampling and *ex situ* gamma spectroscopy analyses; (3) the ability to combine characterization with remediation activities in one fieldwork cycle; (4) improved documentation; and (5) ultimately better remediation, as measured by greater precision in delineating soils that are not in compliance with requirements from soils that are. In addition, the demonstration showed how the use of real-time technologies such as the RadInSoil can be used to facilitate the implementation of a MARSSIM-based final status survey program.

In terms of individual technologies and their performance, the gamma walkover data provided relatively inexpensive, complete coverage of surficial soils with excellent correlation with Ra-226 activity concentrations. The RadInSoil exhibited accuracy for Ra-226 that compared favorably with intralaboratory accuracy results at greatly reduced per-sample costs, while at the same time, yielding acceptable precision for measuring Ra-226 at 5 pCi/g. The *in situ* HPGe systems also produced results that were less costly than *ex situ* gamma spectroscopy analysis of soils samples, while yielding isotope-specific concentrations of comparable quality to *ex situ* analyses. The *in situ* HPGe systems also provided data that were more directly comparable with the definitions of cleanup requirements than data obtained from discrete sample results.

A partial explanation for the excellent performance observed was the fact that the Michigan site was solely contaminated with Ra-226 and its progeny. In some portions of the country, NORM contamination also includes Ra-228. The presence of isotopes from more than one decay series above background complicates the use of the RadInSoil and would also reduce the correlation observed between gamma walkover results and cleanup requirements. However, even when Ra-228 is present, the use of these technologies would still yield a conservative cleanup. The *in situ* HPGe is capable of quantifying Ra-226 and Ra-228 individually, and so would likely play a more important role at sites where both Ra-226 and Ra-228 are of concern.





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## APPENDIX A

This appendix contains summary data tables providing results from the various analytical techniques used at the Michigan site. The data tables are organized by High Purity Germanium (HPGe) data, discrete sample data, and RadInSoil data. Raw gamma walkover results are not included because of the sheer volume of data that was generated.

### HPGe Data

Table A1 provides *in situ* direct measurement HPGe results for pans of soil. Table A1 includes a field identifying the pan, a field identifying the Ra-226 concentration observed, and a field providing the error associated with the concentration estimate. These error estimates are based on counting statistics alone. Table A2 provides *in situ* direct measurement HPGe results for on-site soils. Table A2 includes a field that identifies the location of the measurement, a field identifying the Ra-226 concentration observed, a field providing the error associated with the concentration estimate, and a comment field that gives the context for the measurement. Error estimates are based on counting statistics alone. Table A3 provides *ex situ* HPGe results for Marinelli samples collected from pans. Table A3 includes a field that identifies the pan the Marinelli sample was collected from, a field for the Marinelli sample ID, a field for the Ra-226 concentration observed, and a field providing the error associated with the concentration estimate. Some Marinelli samples were actually composite samples from several sampling locations within the pan, while others represented individual samples. Finally, Table A4 provides *ex situ* HPGe results for Marinelli samples collected from site soils. Table A4 includes a field that identifies the location from which the Marinelli sample was collected, a field for the Marinelli sample ID, a field for the Ra-226 concentration observed, and a field providing the error associated with the concentration estimate.

### Discrete Sample Data

Tables A5, A6, and A7 provide *ex situ* sample analyses conducted by the Analytical Chemistry Laboratory at Argonne National Laboratory (ANL) and by the State of Michigan Department of Environmental Quality. Both laboratories used gamma spectroscopy. In cases where both laboratories analyzed the same sample, the sample was homogenized and split in the field. Table A5 contains information for samples collected from *in situ* soils. These included background samples, samples from selected hot spots, and samples collected as part of the final status survey program. Table A6 contains information for soil samples collected from pans. For pans, either five individual samples were collected (one from the center of the pan and four from the centers of the four quadrants), or one composite sample with the five locations contributing to the composite. Tables A5 and A6 include a field that identifies the sample ID, a field that provides the Ra-226 concentration, the error associated with the concentration, and a purpose field. The purpose field indicates why the sample was collected. Table A7 contains ANL results from radon emanation measurements conducted on background samples and from selected samples from Pan 2. Table A7 includes the sample ID, the

measured Ra-226 concentration for disturbed soils, the measured Ra-226 concentration for soils after a 30-day radon ingrowth period, and the measured percent retention.

### **RadInSoil Data**

Tables A8 through A12 provide results obtained from the RadInSoil instrument. Table A8 contains information for background soil samples. Table A9 contains information for selected hot spots. Table A10 contains information obtained during the final status survey work. Table A11 contains information for selected pans. Table A12 contains replicate information for spots where repeated measurements were taken over time. For every table, reported information includes a sample ID, count time (shielded plus unshielded); estimated Ra-226 concentration correcting for K-40 and Th-232 contributions; estimated Ra-226 concentration neglecting K-40 and Th-232 contributions; miniFIDLER gross activity measurements, if available; and comments.

**Table A1 HPGe Direct Pan Measurements**

Pan No.	Ra-226 (pCi/g)	Error (pCi/g)	Comments
1	30	2	
2	68	4	
3	25	2	
4	38	2	
5	157	4	
6	31	1	
7	14	2	
8	71	3	
9	84	3	
10	317	11	
11	54	3	
12	75	3	
13	35	4	
14	187	9	
15	75	6	
16	96	3	
17	65	3	
18	252	5	
19	129	4	
20	36	3	
21	40	3	
22	30	2	
23	121	3	
24	194	5	
25	183	5	
26	186	5	
27	775	14	
28	1500	31	
29	18	2	
30	16	1	
31	11	1	
32	15	1	
33	22	2	
34	27	2	
34-2	27	2	Duplicate

**Table A2 HPGe Direct Soil Measurements**

Location	Ra-226 pCi/g	Error pCi/g	Comments
BKG4	0.3	0.1	Background Location
1A	1.0	0.2	Final Status Survey Location
1C	1.0	0.2	Final Status Survey Location
1E	2.0	0.3	Final Status Survey Location
1G	0.6	0.2	Final Status Survey Location
1I	0.2	0.1	Final Status Survey Location
5C	0.4	0.1	Final Status Survey Location
6A	0.8	0.2	Final Status Survey Location
6C	0.5	0.1	Final Status Survey Location
6E	0.6	0.1	Final Status Survey Location
6I	4.8	0.3	Final Status Survey Location
HPGe1	6	0.4	Located over H19 (hot spot south of fence) prescraping
HPGe2	2	0.4	Located over H48 prescraping
HPGe3	4.9	0.5	Located over H61 (northwest corner) prescraping
HPGe4	6.3	0.5	Located over H71 (northwest corner) prescraping
HPGe5	1	--	Location is former drum pile. Post scraping.
HPGe6	1	--	Location is former drum pile. Post scraping.
HPGe7	2.4	0.2	HPGe7 was a post-scrapping confirmatory shot over a former hot area in Unit 1.
HPGe8	3.3	0.2	HPGe8 was a post-scrapping confirmatory shot over the former dirt stockpile and adjacent area with yellow flags.
HPGe9	0.2	0.1	Location is near where 100+ bin had been. Post scraping/shoveling.
HPGe10	3.3	0.3	Location is just south of fence. Post scraping.
HPGe12	0.6	0.2	Location is near where 100+ bin had been. Post scraping/shoveling.
HPGe13	2.6	0.3	Location is near where 100+ bin had been. Post scraping/shoveling.
HPGe14	0.8	--	Location is over former pan analysis area. Post shoveling.

**Table A3 HPGe Marinelli Results from Pans**

Pan No.	Marinelli	Ra-226 (pCi/g)	Error (pCi/g)	Comments
3	3AM	11	2	
3	3BM	72	6	
3	3CM	10	1	
3	3DM	189	11	
3	3EM	17	2	
7	7M	17	3	
7	7M(RECOUNT)	11	3	Recount
8	8M	28	5	Composite
9	9M	68	7	Composite
10	10-1M	963	13	
10	10-2M	300	7	
10	10-3M	264	6	
10	10-4M	461	22	
10	10-5M	190	13	
11	11M	927	34	Composite
12	12M	46	4	Composite
13	13M	20	3	Composite
14	14-1M	517	6	
14	14-2M(JQ)	127	8	
14	14-2M(RECOUNT)	122	9	Recount
14	14-3M	79	6	
14	14-4M	64	2	
14	14-5M	59	2	
15	15M	77	6	Composite
16	16M	64	5	Composite
17	17M	53	5	Composite
18	18M	170	8	Composite
19	19M	183	8	Composite
20	20M	22	3	Composite
21	21M	34	4	Composite
22	22M	17	4	Composite
23	23M	45	2	Composite
24	24M	140	3	Composite
25	25M	155	5	Composite
26	26M	182	4	Composite
27	27-1M	1035	9	
27	27-2M	547	9	
27	27-4M	532	25	
27	27EASTM	327	19	
27	27NORTHM	125	11	
27	27-5M	94	3	

**Table A4 HPGe Marinelli Samples from Site Soils**

Location	Marinelli	Ra-226 (pCi/g)	Error (pCi/g)
H07	H07M	248	6
H11	H11M	1	1
H16	H16M	2	1
H18	H18M	17	2
H21	H21M	534	9
H27	H27M	118	4
H28	H28M	668	10
H30	H30M	6	1
H37	H37M	777	12
H38	H38M	98	4
H39	H39M	7	1
H50	H50M	5	1



**Table A5 Discrete Samples from Site Soils**

Sample ID	ANL		DEQ		Purpose
	Ra-226 (pCi/g)	Error (pCi/g)	Ra-226 (pCi/g)	Error (pCi/g)	
BG01	0.49	0.07	0.6	0.4	Background
BG02	0.39	0.08	1.0	0.5	Background
BG03	0.62	0.10	0.7	0.4	Background
BG04	0.51	0.06			Background
BG04 (duplicate)	0.54	0.09			Background
BG05	0.43	0.09	<0.7		Background
BG06	0.61	0.03	0.9	0.4	Background
BG07	0.33	0.06	0.7	0.5	Background
H1A	93.30	4.70	59	2	Hot Spot
H3A	6.31	0.19	1.1	0.7	Hot Spot
H6A	51.30	1.50	237	3	Hot Spot
H7			4.9	0.9	Hot Spot
H8A	1.63	0.07	2.3	2.3	Hot Spot
H9A	9.74	0.10	19.2	19.2	Hot Spot
H10A	0.77	0.12	1.5	1.5	Hot Spot
H11			2.4	0.7	Hot Spot
H12A	2.78	0.11	5.2	5.2	Hot Spot
H13A	6.50	0.25	5.0	0.9	Hot Spot
H16			5.6	0.9	Hot Spot
H18			30	1	Hot Spot
H21			33	1	Hot Spot
H27			6.8	0.7	Hot Spot
H28			6.0	0.7	Hot Spot

**Table A5 (cont.) Discrete Samples from Site Soils**

Sample ID	ANL		DEQ		Purpose
	Ra-226 (pCi/g)	Error (pCi/g)	Ra-226 (pCi/g)	Error (pCi/g)	
H30			17	1	Hot Spot
H37			2240	10	Hot Spot
H38			140	3	Hot Spot
H49			8.7	0.7	Hot Spot
H50			2.8	0.6	Hot Spot
Unit 1A	0.43	0.03			Final Status
Unit 1B	1.62	0.08			Final Status
Unit 1C	1.01	0.12			Final Status
Unit 1D	0.81	0.04			Final Status
Unit 1E	2.12	0.09			Final Status
Unit 1F	0.64	0.06			Final Status
Unit 1G	3.87	0.22			Final Status
Unit 1H	0.37	0.02			Final Status
Unit 1I	0.53	0.04			Final Status
Unit 6A	0.45	0.06			Final Status
Unit 6B	1.18	0.05			Final Status
Unit 6C	1.29	0.16			Final Status
Unit 6D	0.63	0.04			Final Status
Unit 6E	0.54	0.09			Final Status
Unit 6F	0.78	0.04			Final Status
Unit 6G	18.40	0.60			Final Status
Unit 6H	0.84	0.05			Final Status
Unit 6I	1.91	0.07			Final Status

**Table A6 Discrete Samples from Pans**

Sample ID	ANL		DEQ		Purpose
	Ra-226 (pCi/g)	Error (pCi/g)	Ra-226 (pCi/g)	Error (pCi/g)	
Pan 1-1	8.60	0.43	8	1	
Pan 1-2	62.6	1.4	53	2	
Pan 1-3	50.3	1.5	49	2	
Pan 1-4	62.1	1.9	35	1	
Pan 1-5	27.6	1.4	31	1	
Pan 2-1	362	3	49	2	
Pan 2-2	133	2	71	2	
Pan 2-3	63.1	2.2	63	2	
Pan 2-4	57.6	1.4	88	3	
Pan 2-5	57.8	1.1	65	2	
Pan 5			138	3	Composite
Pan 7			14	1	Composite
Pan 8			81	2	Composite
Pan 9			42	1	Composite
Pan 10-1			192	3	
Pan 10-2			508	5	
Pan 10-3			290	5	
Pan 10-4			251	3	
Pan 10-5			206	3	
Pan 11			37	1	Composite
Pan 12			85	2	Composite
Pan 13			22	1	Composite
Pan 14-1			186	3	
Pan 14-2			196	4	
Pan 14-3			284	10	

**Table A6 (cont.) Discrete Samples from Pans**

Sample ID	ANL		DEQ		Purpose
	Ra-226 (pCi/g)	Error (pCi/g)	Ra-226 (pCi/g)	Error (pCi/g)	
Pan 14-4			111	2	
Pan 14-5			116	2	
Pan 15			101	3	Composite
Pan 16			127	2	Composite
Pan 17			89	2	Composite
Pan 18			500	6	Composite
Pan 19			209	3	Composite
Pan 20			39	1	Composite
Pan 21			50	2	Composite
Pan 22			24	1	Composite
Pan 23			48	2	Composite
Pan 24			219	4	Composite
Pan 25			144	3	Composite
Pan 26			207	4	Composite
Pan 27-1			1,480	20	
Pan 27-2			432	6	
Pan 27-3			493	7	
Pan 27-4			1,470	20	
Pan 27-5			247	4	
Pan 28			2,000	20	Composite
Pan 29			22	1	Composite
Pan 30			15	1	Composite
Pan 31			13.6	0.9	Composite
Pan 32			12	1	Composite
Pan 33	15.5	0.8	12.9	0.9	Composite

**Table A7 Radon Emanation Results for Selected Soil Samples**

Sample ID	Ra-226 (pCi/g) Initial Activity		Ra-226 (pCi/g) Equilibrium Activity		Percent Retention
	Activity	Error	Activity	Error	
BG01	0.33	0.02	0.47	0.02	70.1
BG02	0.33	0.02	0.44	0.02	73.7
BG03	0.37	0.02	0.68	0.04	54.4
BG04	0.32	0.02	0.48	0.02	66.6
BG05	0.32	0.02	0.54	0.02	58.6
BG06	0.43	0.02	0.79	0.02	54.6
BG07	0.33	0.02	0.45	0.02	72.4
BG07 (duplicate)	0.25	0.02	0.38	0.02	65.3
PAN2-1	267.9	3.2	287.2	3.4	93.3
PAN2-2	178.2	2.0	180.3	2.0	98.8
PAN2-3	57.3	0.7	60.6	0.7	94.6
PAN2-4	56.9	0.6	64.3	0.7	88.5
PAN2-5	57.9	0.6	64.1	0.7	90.3

**Table A8 RadInSoil Data for Background Soil Locations**

Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th	miniFIDLER (cpm)
BG1	10/13/98	10:10	300	0.27	1.54	
BG2	10/13/98	10:20	300	0.41	1.68	
BG3	10/13/98	10:45	300	0.60	1.87	
BG4	10/13/98	11:05	300	0.33	1.60	575
BG5	10/13/98	11:35	300	0.51	1.78	
BG6	10/13/98	11:20	300	0.65	1.92	
BG7	10/13/98	10:30	300	0.59	1.86	

**Table A9 RadInSoil Data for Selected Hot Spot Locations**

Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th	miniFIDLER (cpm)	Comments
H1	10/14/98		300	19.15	20.41	4,800	
H2	10/14/98		300	58.76	60.03	12,000	
H3	10/14/98		300	9.22	10.49	16,000	
H4	10/14/98		300	118.34	119.61	30,000	
H5	10/14/98		300	127.08	128.35	31,000	
H6	10/14/98		300	185.36	186.63	80,000	
H7	10/14/98	15:00	300	116.33	117.60	21,000	
H7	10/19/98	10:30	300	135.02	136.29	21,000	Repeat
H7	10/20/98	11:02	300	133.85	135.12	21,000	Repeat
H8	10/14/98		300	24.62	25.89	15,000	
H9	10/14/98		300	6.72	7.99	2,200	
H10	10/14/98		300	-0.22	1.05	2,200	
H10	10/14/98		600	0.24	1.51		
H11	10/14/98		600	6.86	8.13	1,900	
H11	10/14/98		300	6.47	7.74		
H11	10/14/98	18:55	300	5.85	7.12		
H12	10/14/98		300	3.38	4.64	1,800	
H13	10/14/98		300	3.89	5.16	2,500	
H14	10/14/98		300	1.78	3.04	1,000	
H14A	10/21/98	09:48	300	6.05	7.32	2,100	12 in. E of H14
H15	10/15/98	09:05	300	11.89	13.16	4,500	
H16	10/15/98	09:17	300	2.42	3.69	1,000	
H17	10/15/98	08:50	300	0.60	1.87	600	
H18	10/19/98	10:45	300	19.61	20.88		
H18	10/19/98	15:55	300	20.43	21.70	5,000	Moved 3 in. N
H19	10/19/98	10:57	300	14.04	15.31	4,000	
H20	10/19/98	11:10	300	10.49	11.76		
H20	10/19/98	15:40	300	17.24	18.50	4,400	Moved 6 in. W
H21	10/19/98	11:25	300	9.86	11.13		
H21	10/19/98	14:45	300	162.41	163.68	41,000	Moved 7 in. SW
H22	10/19/98	12:33	300	117.30	118.57	32,000	
H23	10/19/98	15:03	300	37.06	38.33	9,000	
H24	10/19/98	15:20	300	146.16	147.43	29,000	
H25	10/19/98	16:34	300	0.96	2.23	600	

**Table A9 (cont.) RadInSoil Data for Selected Hot Spot Locations**

Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th	miniFIDLER (cpm)	Comments
H26	10/19/98	16:47	300	1.76	3.03	800	
H27	10/19/98	17:02	300	62.94	64.21	14,200	
H28	10/19/98	17:15	300	273.35	274.62	42,000	
H29	10/19/98	17:28	300	82.93	84.20	25,000	
H30	10/20/98	11:19	300	7.73	9.00	2,300	
H31	10/20/98	11:36	300	136.77	138.04	36,000	
H32	10/20/98	11:49	300	52.76	54.03	12,000	
H33	10/20/98	12:10	300	78.14	79.41	24,000	
H34	10/20/98	16:12	300	88.91	90.18	23,000	
H35	10/20/98	16:25	300	38.40	39.67	12,000	
H35A	10/20/98	16:40	300	60.81	62.07	13,000	10 in. NE of H35
H37	10/20/98	16:53	300	928.64	929.90	258,000	
H38	10/21/98	09:04	300	91.58	92.85	24,000	
H45	10/21/98	13:43	300	6.05	7.31	2,100	
H48	10/20/98	17:12	300	129.45	130.72	33,000	
H49	10/21/98	09:32	300	7.78	9.05	2,300	
H49	10/21/98	13:25	300	8.43	9.69		Repeat
H50	10/21/98	12:21	300	2.75	4.02	1,600	
H51	10/21/98	14:00	300	1.73	3.00	1,000	
H52	10/21/98	12:01	300	10.38	11.65	2,800	
H61	10/20/98	17:28	300	125.90	127.17		
H69	10/21/98	11:10	300	7.41	8.68	2,500	
H71	10/20/98	17:40	300	22.70	23.97		
H76	10/21/98	10:20	300	11.20	12.46	3,200	
H77	10/21/98	10:45	300	14.04	15.31	3,100	
H520	10/21/98	11:45	300	10.98	12.25	2,900	



**Table A10 RadInSoil Data for Final Status Survey Units**

Unit ID	Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th
1	1A	10/22/98	10:21	300	0.53	1.80
	1B	10/22/98	10:35	300	0.43	1.70
	1C	10/22/98	10:47	300	0.77	2.04
	1D	10/22/98	11:21	300	9.62	10.88
	1E	10/22/98	11:10	300	1.12	2.39
	1F	10/22/98	10:58	300	0.62	1.89
	1G	10/22/98	11:33	300	0.55	1.82
	1H	10/22/98	11:45	300	0.04	1.31
	1I	10/22/98	NA	300	0.57	1.84
2	2A	10/22/98	12:10	300	0.57	1.84
	2B	10/22/98	12:26	300	0.51	1.78
	2C	10/22/98	12:37	300	0.64	1.91
	2D	10/22/98	13:21	300	1.40	2.67
	2E	10/22/98	13:07	300	1.26	2.53
	2F	10/22/98	12:50	300	1.27	2.54
	2G	10/22/98	13:34	300	0.33	1.60
	2H	10/22/98	13:45	300	0.36	1.62
	2I	10/22/98	13:57	300	0.29	1.56
3	3A	10/22/98	08:31	300	1.00	2.27
	3B	10/22/98	08:44	300	0.46	1.73
	3C	10/22/98	08:55	300	2.67	3.93
	3D	10/22/98	09:30	300	0.59	1.86
	3E	10/22/98	09:18	300	0.37	1.64
	3F	10/22/98	09:06	300	1.20	2.47
	3G	10/22/98	09:42	300	0.31	1.58
	3H	10/22/98	09:54	300	0.99	2.26
	3I	10/22/98	10:08	300	0.27	1.54
4	4A	10/22/98	15:44	300	1.08	2.35
	4B	10/22/98	15:32	300	0.71	1.98
	4C	10/22/98	15:20	300	0.68	1.95
	4D	10/22/98	14:44	300	0.63	1.90
	4E	10/22/98	14:57	300	0.85	2.12
	4F	10/22/98	15:08	300	0.39	1.66
	4G	10/22/98	14:32	300	0.82	2.09

**Table A10 (cont.) RadInSoil Data for Final Status Survey Units**

Unit ID	Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th
	4H	10/22/98	14:20	300	0.52	1.79
	4I	10/22/98	14:07	300	0.82	2.08
5	5A	10/23/98	10:12	300	0.49	1.76
	5B	10/23/98	10:23	300	0.85	2.11
	5C	10/23/98	10:36	300	0.51	1.78
	5D	10/23/98	11:14	300	0.86	2.13
	5	10/23/98	11:01	300	0.65	1.92
	5F	10/23/98	10:49	300	0.81	2.07
	5G	10/23/98	11:26	300	0.42	1.69
	5H	10/23/98	11:38	300	0.53	1.80
	5I	10/23/98	11:50	300	1.97	3.24
6	6A	10/22/98	17:44	300	0.34	1.61
	6B	10/22/98	17:32	300	0.94	2.21
	6C	10/22/98	17:14	300	0.49	1.76
	6D	10/22/98	16:23	300	0.73	2.00
	6E	10/22/98	16:36	300	0.46	1.72
	6F	10/22/98	16:48	300	0.73	2.00
	6G	10/22/98	15:57	300	5.23	6.50
	6H	10/22/98	16:08	300	0.75	2.02
	6I	10/22/98	17:02	300	2.05	3.32
7	7A	10/23/98	09:24	300	0.41	1.68
	7B	10/23/98	09:46	300	0.52	1.79
	7C	10/23/98	09:58	300	0.65	1.92
	7D	10/23/98	09:13	300	0.62	1.89
	7E	10/23/98	08:59	300	0.84	2.11
	7F	10/23/98	08:47	300	0.45	1.72
	7G	10/23/98	08:05	300	0.42	1.69
	7H	10/23/98	08:17	300	1.41	2.67
	7I	10/23/98	08:31	300	0.60	1.87
8	8A	10/23/98	12:03	300	0.79	2.06
	8B	10/23/98	12:14	300	0.92	2.18
	8C	10/23/98	12:25	300	0.45	1.72
	8D	10/23/98	12:47	300	0.78	2.05
	8E	10/23/98	12:36	300	0.58	1.84

**Table A10 (cont.) RadInSoil Data for Final Status Survey Units**

Unit ID	Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th
	8F	10/23/98	12:59	300	0.29	1.56
	8G	10/23/98	13:44	300	0.41	1.68
	8H	10/23/98	13:55	300	0.72	1.99
	8I	10/23/98	13:11	300	1.13	2.39

**Table A11 RadInSoil Data for Selected Soil Pans**

Location	Date	Time	Measurement Time (seconds)	Ra-226 (pCi/g) adjusted for K & Th	Ra-226 (pCi/g) not adjusted for K & Th
Pan1-1	10/14/98	~12:00	300	25.25	26.52
Pan1-2	10/14/98		300	49.35	50.61
Pan1-3	10/14/98		300	51.55	52.82
Pan1-4	10/14/98		300	28.04	29.31
Pan1-5	10/14/98		300	22.30	23.57
Pan2-1	10/14/98	~13:00	300	95.23	96.49
Pan2-2	10/14/98		300	60.47	61.74
Pan2-3	10/14/98		300	57.11	58.37
Pan2-4	10/14/98		300	45.35	46.62
Pan2-5	10/14/98		300	60.30	61.57
Pan10-1	10/15/98	15:53	300	520.66	521.92
Pan10-2	10/15/98	16:05	300	269.79	271.06
Pan10-3	10/15/98	16:45	300	197.22	198.49
Pan10-4	10/15/98	16:33	300	278.75	280.02
Pan10-5	10/15/98	16:20	300	191.84	193.11
Pan14-1	10/16/98	10:07	300	821.26	822.53
Pan14-2	10/16/98	10:21	300	147.09	148.35
Pan14-3	10/16/98	10:52	300	257.05	258.31
Pan14-4	10/16/98	11:03	300	87.80	89.07
Pan14-5	10/16/98	11:34	300	89.92	91.19
Pan27-1	10/20/98	12:28	300	747.09	748.35
Pan27-2	10/20/98	12:42	300	329.81	331.08
Pan27-3	10/20/98	12:56	300	526.33	527.60
Pan27-4	10/20/98	13:10	300	637.83	639.10
Pan27-4A	10/20/98	13:22	120	720.39	721.66
Pan27-5A	10/20/98	13:28	120	258.88	260.15
Pan27-5	10/20/98	13:34	300	264.78	266.05
Pan27-E	10/20/98	13:34	120	215.85	217.12
Pan27-W	10/20/98	13:54	120	1325.63	1326.90
Pan27-S	10/20/98	14:00	120	198.62	199.88
Pan27-N	10/20/98	14:07	120	313.44	314.71
Pan28-1	10/20/98	14:22	120	1293.24	1294.51

**Table A12 RadInSoil Results for Replicate Measurements**

Location	Date	Time	Measurement Duration (seconds)	Corrected Ra-226 (pCi/g)	Uncorrected Ra-226 (pCi/g)	miniFIDLER (cpm)
BG4	10/13/98	15:15	600	0.37	1.64	575
		15:37	600	0.54	1.81	575
		16:00	600	0.53	1.80	575
		16:20	600	0.44	1.70	575
		16:50	600	0.44	1.71	575
		17:15	600	0.56	1.83	575
		17:37	600	0.24	1.51	575
	10/14/98	08:21	600	0.67	1.94	575
		08:54	600	0.49	1.76	575
		09:15	600	0.51	1.78	575
		09:37	600	0.61	1.88	575
		10:17	300	0.32	1.59	575
		10:30	300	0.45	1.72	575
		10:45	300	0.47	1.74	575
	10/15/98	08:20	300	0.39	1.66	575
		09:53	300	0.50	1.77	575
		10:07	300	0.67	1.94	575
		10:17	300	0.34	1.61	575
		10:30	300	0.61	1.88	575
		10:40	300	0.83	2.10	575
		10:53	300	0.35	1.62	575
		11:03	300	0.79	2.05	575
	10/19/98	09:59	300	0.88	2.15	575
	10/20/98	10:35	300	0.33	1.59	575
	10/21/98	8:15	300	0.60	1.87	575
H11	10/15/98	08:35	300	6.81	8.08	575
		13:36	300	6.42	7.69	575
		13:47	300	7.13	8.40	575
		13:59	300	6.36	7.63	575
		14:10	300	6.48	7.75	575
		14:21	300	6.83	8.10	575
		14:32	300	5.93	7.20	575
		14:43	300	6.48	7.74	575
		14:54	300	6.61	7.88	575
		15:05	300	6.60	7.87	575
		15:16	300	6.63	7.89	575
		17:50	300	6.29	7.56	575
	10/16/98	08:59	300	6.40	7.67	575
	10/19/98	10:15	300	6.43	7.69	575
		17:40	300	6.92	8.19	575
	10/20/98	10:50	300	7.06	8.33	575
		17:55	300	6.70	7.97	575
	10/21/98	08:40	300	6.75	8.01	575
		17:04	300	7.04	8.31	575

**Table A12 (cont.) RadInSoil Results for Replicate Measurements**

Location	Date	Time	Measurement Duration (seconds)	Corrected Ra-226 (pCi/g)	Uncorrected Ra-226 (pCi/g)	miniFIDLER (cpm)
	10/22/98	08:05	300	6.31	7.58	575
		08:17	120	6.36	7.63	575
		17:56	120	7.08	8.35	575
		18:01	120	6.88	8.14	575
		18:06	120	6.97	8.24	575
		18:10	120	6.38	7.65	575
		18:15	120	7.09	8.36	575
		18:19	120	6.37	7.64	575
		18:26	120	6.20	7.47	575
H11	10/22/98	18:32	120	6.89	8.16	575
		18:36	120	6.74	8.01	575
		18:41	120	7.14	8.41	575
		18:46	300	6.82	8.09	575
	10/23/98	07:47	300	6.35	7.62	575